THE PRODUCTS AND STRUCTURE OF KILAUEA

BY

JOHN B. STONE

BERNICE P. BISHOP MUSEUM

BULLETIN 33

PUBLISHED BY THE MUSEUM
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TOPOGRAPHY

Kilauea crater is in the southeastern part of the island of Hawaii, 30 miles southwest of the harbor and city of Hilo. West-northwest of the crater is Mauna Loa (elevation 13,675 feet), an enormous gently-sloping dome 22 miles away; to the north is the cone-covered summit of Mauna Kea (elevation 13,784 feet), 32 miles away; to the southwest are the buttes of Mohokea, and still farther on is the ocean. Lava flows from Kilauea and its subordinate cones and fissures cover a four-sided area 52 miles long and 18 miles wide and comprising that part of the island of Hawaii lying southeast of a line extending approximately from Punaluu to the coast, about six miles southeast of Hilo. (See fig. 1.)

Within the area covered by lava flows from Kilauea, there has been practically no erosion. Rain sinks so rapidly through the fissured, porous, and cavernous lavas that the water table is very low. There are no permanent streams or springs even in the rainy part of the area, although brackish water can be found along the coast in a few cracks that reach down to sea level. Nevertheless, the unconsolidated ash deposits have been considerably eroded except where they are protected by vegetation. The torrential Kona rains cut trenches in the ash-covered slopes, and the strong trade winds are continually carrying the finer sand southwestward, where it forms widespread deposits. On days of unusually strong wind, dust clouds are carried out a mile or more over the ocean. In southern Kau below the great Hilina pali, an area a mile and a half long at its maximum about half a mile wide, is covered to a depth of several feet by angular bowlders and gravel which have been brought down by storm—water and landslides from the pali. Some of the fine sand from this bowlder plain has been blown to the southwest, where it forms sand dunes, many of which have the form of barchanes. Gravity is the chief transporting agent in many parts of the Kau desert and is rendered especially efficient by the fissured character of the lava flows. In some places the surface is littered with angular frag-

ments, many about the size of paving blocks, which make walking very tiresome.

But the total topographic effect of this erosion is insignificant. All the major features of the topography and most of the minor features are those of lava eruptions and faulting.

To an observer standing at the Uwekahuna triangulation station (elevation 4,090 feet) it is at once apparent that Kilauea is separate from Mauna

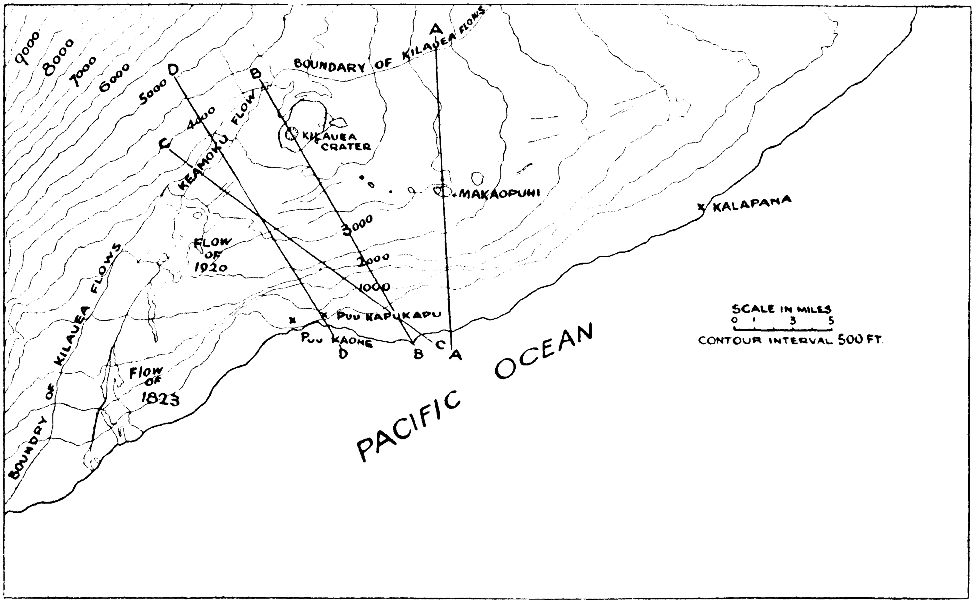

FIGURE 1. Map of southeastern Hawaii. Lettered lines A-A, B-B, C-C, D-D, show the position of cross sections described in figure 5.

Loa. Between Uwekahuna and the Mauna Loa slope is a broad, open valley, down which the pre-historic Keamoku flow turned after it reached the Kilauea boundary. (See fig. 1.) A sudden change of slope at the intersection of the Mauna Loa and Kilauea domes all the way to the ocean is a conspicuous feature of the topographic maps. This topographic boundary is followed by the Kau-Volcano House road from a point about two miles northeast of Pahala to the Kapapala "halfway house." In many places along this road the nearly flat lava fields of Kilauea abut against a small pali[1] at the foot of the Mauna Loa slope. In places two or more

[1] A number of Hawaiian words appear as proper names on the topographic maps of the United States Geological Survey. Common ones are: *kipuka* (an island-like area surrounded by one or more lava flows), *puu* (hill), and *lua* (pit or crater). The terms pahoehoe and aa distinguish two types of lava that are in general use in geological writing and do not need definition here.

palis form a terraced slope, in others the palis have been almost completely obliterated by flows from Mauna Loa. North of Kilauea crater the bounding escarpment dies away near the crest of the Kilauea dome, and from that point to the seacoast southeast of Hilo there is no marked topographic break between Kilauea and Mauna Loa.

Kilauea crater itself is a depressed area in the summit of a dome, which slopes away in all directions. It is shut in on all sides except the south by perpendicular cliffs which reach a maximum height of 450 feet on the northwest side. In places, notably southwest of Uwekahuna and at the Volcano House, are terraces formed by fault blocks. The south rim of the crater is a low cliff partly concealed by ash deposits. At two points the south wall of the depression is very low, and in 1921 short streams of lava from Kilauea overflowed into the Kau desert. The crater floor is itself a gently

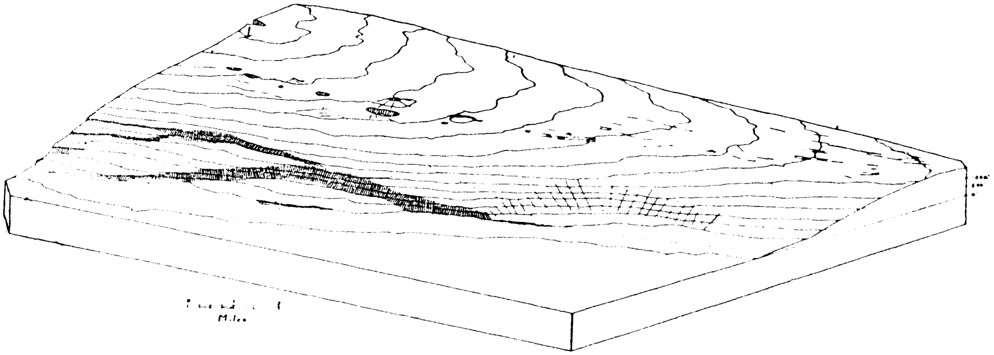

FIGURE 2. Block diagram of the Puna ridge showing pit craters, cones, fissures, and fault cliffs.

sloping lava dome having at its summit the yawning pit of Halemaumau, 3,400 by 3,000 feet across and 1,350 feet deep (in 1925). The only irregularities of the floor are minor domes and a few small spatter cones on lava flows.

Extending southeast from Kilauea and gradually curving around to the northeast is a broad ridge or nose reaching all the way to Cape Kumukahi, the easternmost point of Hawaii. (See fig. 2.) Following the summit of this ridge quite closely is a line of pit craters, lava cones, and fissures. The pit craters are straight-sided depressions usually with a roughly circular or elliptical outline. They are all subsidence craters formed by collapse in a flat terrane and are not summit craters of cones. Their upper walls are cliffs composed of horizontal lava flows; the bottoms of most of them are talus funnels, but a few have level floors formed by the cooling of lava lakes. The line beginning with Keanakakoi includes twelve of these pits

ranging in dimensions from the Devil's Throat, 35 feet in diameter and 250 feet deep, to Makaopuhi, a mile long and nearly 1,000 feet deep. Kilauea Iki, another large crater, lies east of Kilauea, not in the chain of pits.

Most of the lava cones and cinder cones lie east of the pit craters. The largest is the 400-foot cinder cone at Kapoho. Another large one is the flat dome of Kane Nui o Hamo, a cone 300 feet high with a summit crater as deep as the cone is high. Following the line of craters and cones through Puna are many series of parallel cracks, gaping fissures, some as much as 50 feet across.

From Kilauea southwest to the sea the country slopes quite regularly. Striking parallel with the slope are many open fissures, along some of which there has been enough vertical displacement to form small cliffs. One such cliff, Puu Nahala, is somewhat over 100 feet high. Several lava and cinder-cones are conspicuous features along this rift line. The Kamakaia Hills are especially large and symmetrical, the largest being 150 feet high. In detail the surface is rough because of its covering of fresh flows, either hummocky, irregular pahoehoe or jagged, bristling aa.

For about six miles south of Kilauea the country has a regular southerly slope, interrupted only by a few small inward-facing fault cliffs. In the remaining three miles or so to the sea the land falls off about 2,000 feet in a series of giant terraces bordered by cliffs as much as 1,500 feet high. The coast-line itself is nearly everywhere a cliff, usually 20 or 30 feet high, but at Puu Kapukapu 1,000 feet high. Most of the smaller cliffs are covered by cascading lava flows. Aa flows are especially numerous coming down over the cliffs in Puna. Wave erosion is now cutting back the coast, but its total effect is slight. Deep water comes to the shore in most places.

CLIMATE AND VEGETATION

The climate of the Kilauea-Kau-Puna region varies remarkably. The prevailing northeast trade winds bring abundant rain to the portion of the area north of the Puna ridge. At Hilo the average annual rainfall is 139 inches, but it decreases at altitudes above 3,200 feet and is only 88 inches at the Volcano House. Humidity is high, at the Volcano House often 100 per cent. In striking contrast is the leeward portion of the area, south of the line. In the Kau desert southwest of Kilauea the rainfall is so small that vegetation is nearly absent and dust storms may be seen when it is raining at the Volcano House three miles away. In general the parts of the area that slope to the south and southwest are poorly watered. What rain they receive is mostly brought by the southwest or "Kona" winds which blow occasionally, especially during the winter.

The temperature of Hawaii is equable and in spite of the sub-tropical latitude is never extremely high. At Hilo the mean annual temperature is 72° with a range from 65° to 79.5° (mean minimum and maximum). Temperature decreases with increasing altitude so that the air at the Volcano House is usually invigorating and the nights are uniformly cool. The mean annual temperature is 61° ranging from 54° to 68°. Light frosts occur rarely.

The climatic variation is strikingly evident in the vegetation. The whole windward slope is covered by a dense forest, in many places impenetrable except along trails. At lower altitudes the forest is made up of strictly tropical trees, among which are the kukui, the hala or screw-pine, the banana, the breadfruit, the mango, and the guava. Along the coast are coconut palms, in places in large groves. At higher altitudes this tropical forest is gradually replaced by tree-ferns and the lehua, which form nearly the whole forest above 2,000 feet. A few sandalwood trees and a few koa grow near the volcano, but the koa thrives better at higher altitudes. Climbing plants like the ieie and the uluhi (staghorn fern) form entanglements in many places.

On the lee side of the area the forest thins rapidly. Along the south coast as far west as Kamoamoa are scattered groves of coconut palms and hala trees and thickets of guava bushes, but the coast west of Kamoamoa and nearly all the district of Kau are thinly wooded. Large areas are covered by barren lava flows with only a few scattered lehua trees. Soil is limited to patches of volcanic ash, but in all except the most arid spots grass grows wherever it can take root.

POPULATION

Eastern Puna has a number of inhabitants especially around the sugar plantations near Kapoho and Pahoa. Cattle are pastured on some of the lands unfit for cultivation. Only a few people live in the rest of the area. Near the Volcano House are the military recreation camp and a number of summer cottages, but the triangular area between Punaluu, Kilauea crater, and Kalapana is entirely uninhabited and, except for cattle on the flats south of Pahala, is abandoned to the wild goats and donkeys.

PREVIOUS WORK

Since 1823, when Kilauea was visited by a party of missionaries, there has been some sort of record of the activities of the volcano and since the establishment of the Hawaiian Volcano Observatory in 1912 the record has been detailed and complete. The work of the Observatory, however, has

been largely restricted to recording the present-day changes of the volcano; and most geologists who have visited Kilauea during the century since 1823 have been forced by the shortness of the time at their disposal and by the lack of a large-scale topographic map to confine their observations to the immediate neighborhood of the crater. Consequently no detailed geological study of the whole area has yet appeared, although much has been written about the volcanoes of Hawaii, and about Kilauea in particular.

The most important writers treating of the general geology and petrology of Kilauea are: Brigham (4),[2] Cross (8), Daly (10), Dana (11), Dutton (12), Hitchcock (17), Jaggar (20), and Washington (38). Purely volcanological papers are omitted.

The first systematic geological work on Hawaii was begun in 1920 by L. F. Noble (28)[3] and W. O. Clark in studying the water resources around Pahala, Kau district. Their work showed that the lavas in the Pahala district, which is on the flank of Mauna Loa, can be divided into three series. The first two series are separated by a profound unconformity. This successful demonstration of distinct epochs in the life of Mauna Loa offered the first definite hope for the solution of the geology of Hawaii.

ACKNOWLEDGMENTS

During the summer and fall of 1925 I spent five months on the island of Hawaii, mostly in the area discussed in this paper. My study was made possible by a Bishop Museum Fellowship awarded by Yale University, and this paper has already been presented as a dissertation in candidacy for the degree of Doctor of Philosophy at Yale.

The problem was outlined by Professor Herbert E. Gregory. While in the field I received assistance from a great many friends, among them Mr. and Mrs. W. F. Stephens, Mr. B. M. Sumner, and Mr. A. M. Brown, Jr., whose courtesy and that of many others it is a real pleasure to acknowledge. I am especially indebted to Dr. T. A. Jaggar, Jr., and Mr. R. H. Finch of the Hawaiian Volcano Observatory, who did everything possible to help me and from whose suggestions I have profited greatly. Mr. W. O. Clark guided me on several field trips to Kau and discussed some of the problems with me.

In preparing this paper I have had the helpful advice of Professor Adolph Knopf of Yale University. A number of thin sections were made for me by the United States Geological Survey. Dr. C. K. Wentworth kindly loaned me his apparatus for constructing block diagrams.

[2] Numbers in parentheses refer to Bibliography on page 58.

[3] In 1924, H. T. Stearns studied the geology of the Kau district. His report probably will include the results of work by Noble, Clark, and others.

THE LAVAS

INTRODUCTION

Hawaii, like the other islands of the group, is entirely volcanic. With the exception of the trachytes of Puuwaawaa and Puu Anahulu (7) and the possible oligoclasite of Waimea (38, p. 477), the lavas are all basaltic, for the most part ordinary feldspar basalts and augite andesites but with some more basic varieties. Fragmental layers form a very small proportion of the island, and dikes or other intrusive bodies are few and small.

There are five recognized centers of eruption, of which two, Kohala and Mauna Kea, have been inactive for at least several hundred years. Kohala seems to be much the older. Hualalai has been inactive since 1801, but Mauna Loa and Kilauea have been active during most of their recorded history, although both were quite dormant in 1925. The windward slopes of Kohala are dissected by deep gulches, and so to a less extent are those of Mauna Kea, but no study has been made of the rocks of the lowest flows. The other volcanoes are practically untouched by erosion so that the only sections exposed are in fault cliffs.

It is generally assumed in discussions of Hawaii that the island has been built by the five recognized volcanoes, but this is by no means certain. An old land mass underlies Kilauea and at least part of Mauna Loa. That this land mass was built by the present Mauna Loa is quite possible but not proven. The evidence of extensive faulting along the southern coast and probably also along the northern side of Kohala suggest that there may have been older volcanic centers of which nothing is known, now sunk beneath the ocean or buried by the later volcanoes.

CLASSIFICATION

The classification of basic lavas has been treated with especial reference to Hawaii by Washington (38, pp. 465-474), whose conclusions are summarized here. Lavas composed essentially of plagioclase and pyroxene, with or without olivine, in the proportions in which they occur in Hawaiian rocks, may be divided into three great classes; andesite, basalt, and more basic rocks, depending on the relative proportions of salic and femic minerals. The arbitrary limits set for the groups by Washington are: andesite, salic minerals (almost entirely plagioclase) 87.5 to 62.5 per cent; basalt, salic minerals 62.5 to 37.5 per cent; more basic rocks, less than 37.5 per cent. The groups andesite and basalt are again divided on the basis of the composition of the plagioclase. When the plagioclase of a basalt is not speci-

fied, it is assumed to be labradorite. Finally the presence or absence of olivine makes possible another subdivision of these two groups; but the term "basalt" is not limited to olivine-bearing lavas. The more basic rocks are divided into two groups, one in which the percentage of salic minerals is between 37.5 and 12.5, and an ultrabasic group with less than 12.5 per cent of salic minerals. The group containing 37.5 to 12.5 per cent of salic minerals is represented in Hawaii only by a class of lavas rich in olivine; these lavas are called "picrite basalts." The ultrabasic group is not represented. It should be noted that in Washington's scheme the ratio of salic to femic minerals, as well as the composition of the plagioclase, is that calculated in the norm.

The arbitrary limits set by Washington for the groups, such as andesite and basalt, may not have general validity, but they probably coincide closely with ordinary usage. For the rather uniform rocks of Kilauea the fundamental division into the three varieties, labradorite basalt, olivine-labradorite basalt, and picrite basalt, has been well brought out by Washington's analyses and could not be brought out by any other method in the common glassy lavas. In the present paper I have classified lavas by correlation with analyses given by Washington. The method presents no difficulty when applied to the Kilauean lavas because the distinction between basalt and olivine basalt depends on a modal characteristic, the presence or absence of olivine; and the only rocks more basic than basalts are picrite basalts, which can also be recognized by their high content of modal olivine. Accordingly rocks with less than 2 per cent of olivine are classed as basalts, those with more than 2 per cent and less than 15 per cent as olivine basalts, and those with more than 15 per cent as picrite basalts. The boundary between olivine basalt and picrite basalt is somewhat uncertain as the only olivine basalt analyzed by Washington (38, pp. 342-344) has 7.47 per cent of olivine in the norm and about 12 per cent in the mode. The other analysis given in the same place as of an olivine basalt is that of a specimen collected by Cross (8, p. 42) and said by him to be poor in olivine. The compositions of the plagioclases given in the present paper are those in the mode.

Comparison of the mineral compositions given in this paper and the norms calculated by Washington shows that the percentage of feldspar is much lower in the mode than in the norm; but the data are not sufficient to correlate the modal and normative compositions. It is plainly desirable to determine the actual mineral composition of rocks analyzed chemically, so that they can be used as standards of reference. Unfortunately micrometric measurements of basalts are all too rare in geological literature; the only previous ones for Hawaii are those given by Daly (9, pp. 292, 296,

302). On the chemical and mineral composition of basalts of the Arctic region Holmes (19) has reported.

Kilauea is built of superposed lava flows with a few interbedded deposits of fragmental material. The flows are divided into two series; an older series, here called the pre-Kilauea series, consisting of horizontal flows with a conspicuous ash bed (the Pahala ash) at its top; and the younger or Kilauea series lying unformably on the pre-Kilauea series.

THE PRE-KILAUEA SERIES

The pre-Kilauea series is exposed in some of the high cliffs in southern Puna and Kau. A section of nearly 1,500 feet is exposed in Hilina pali and a section of 1,000 feet in the seaward face of Puu Kapukapu, but unfortunately most parts of these cliffs are inaccessible. The series consists of horizontal flows and ash beds cut by a few small dikes. The ash beds, which are thin and discontinuous, make up perhaps five per cent of the section. Aa flows with clinkery tops and a maximum thickness of about 20 feet predominate.

The massive portions of the aa flows are light or medium gray, aphanitic rocks having a few small distorted vesicles. Some are aphyric except for very sparse rounded microphenocrysts of olivine. Another common type has feldspar phenocrysts as much as two millimeters long. A thin section of this type of rock showed a few microphenocrysts of a brownish augite in addition to laths or groups of laths of a sodic bytownite ($Ab_{22}An_{78}$). The ground mass is very fine grained with intersertal texture and a very little glass.

The ash at the top of the pre-Kilauea series is correlated with the Pahala ash of western Kau. (See p. 23.) The underlying flows and ash beds therefore correspond in stratigraphic position with the Pahala and pre-Pahala series as defined by Noble and Clark. In the cliffs of eastern Kau and western Puna, however, there is no break in the older lavas, nor are any ashes interbedded with the later flows, but the uppermost bed of ash appears to be faulted. The Pahala series in eastern Kau apparently lies conformably on the pre-Pahala series. The following description of the type pre-Pahala and Pahala series is based on Noble's manuscript report, as quoted by Washington (38, pp. 119-121):

> . . . . the pre-Pahala series consists chiefly of massive, rather uniformly bedded flows, most of which range in thickness from 6 to 25 feet. The series includes a few beds of stratified yellow ash, none over 15 feet thick and most much thinner. The prevailing color of the lavas is light bluish or pinkish gray contrasting with the very dark recent and historic lavas. Much the greater number belong to one general type, consisting mainly of plagioclase, augite, and subordinate magnetite, with olivine rather sparingly present.

Lavas of the Pahala series are in general medium to rather dark bluish-gray rocks, lighter in color than most of the historic and recent flows, but much darker than most of the pre-Pahala lavas, and lacking the pinkish tints that many of the pre-Pahala rocks show. The dominant type is plagioclase-augite basalt moderately poor to moderately rich in olivine. The Pahala series is characterized by beds of stratified yellow ash, one at least 75 feet thick in places, another at least 50 feet.

The Pahala series is exposed at a number of places along the northwest edge of the Kilauea area. The pre-Pahala series is exposed in the walls of Mohokea and Wood Valley. The description by Noble of the pre-Pahala series agrees well with the rocks in the lower part of the cliffs of eastern Kau. In the upper third of the cliffs ash beds are more important, and most of the flows examined are pahoehoe lavas much like the dark lavas of the Kilauea series. This agrees with the description of the Pahala series.

The source of the pre-Pahala and Pahala series, and therefore of the corresponding pre-Kilauea series, was a volcano in the general vicinity of Mauna Loa. This origin is proved by the dips in the Pahala region and by the observations of Clark (5) that the older series of lavas are found on the slopes of Mauna Loa up to an elevation of at least 7,500 feet.

THE KILAUEA SERIES

The Kilauea series includes all lavas and ash beds of the Kilauea area which are younger than the Pahala ash, with the exception of some post-Pahala flows from Mauna Loa, which interfinger with the Kilaueau flows along the contact of the two domes. The Kilauea series covers the surface of the entire area except the cliffs and kipukas where the pre-Kilauea series is exposed, and is well displayed in a number of places (fig. 1). A section 450 feet thick appears in the walls of Kilauea crater and other sections are exposed in the pit-craters of Puna, the thickest being 700 feet in the crater of Makaopuhi. The Kilauea series probably has a maximum thickness of at least 1,000 feet. In the southern part of the area, however, there is little evidence of the thickness. Sections as much as 100 feet thick in the face of Puu Nahaha and in the Great Crack do not expose the base of the Kilauea series. In some places along the tops of the big cliffs the Kilauea flows overlying the Pahala ash have a total thickness of less than 100 feet.

With the exception of the Uwekahuna ash and the surface ash around the crater, the Kilauea series consists entirely of lavas, pahoehoe flows being much more numerous than aa. Complete mapping of the individual flows is impracticable because of the ash and forest cover, which hides a large part of the region. It is extremely difficult to separate pahoehoe flows even in the desert country when once the younger ones have lost their fresh appearance. The topographic maps of the United States Geological Survey show

all the historic flows and also most of the areas covered by aa, although individual aa flows as a rule are not outlined. The flows mapped vary greatly in size, ranging from the flow of 1868 with an area of about 31 acres to the great floods of 1823, 1920, and the Kamooalii flow with areas of 5, 5.2, and about 10 square miles, respectively. The older flows apparently had a similar range of size.

The flows of the Kilauea series can be divided into a number of groups depending on their relative ages and distribution.

Flows in the Walls of Kilauea and the Pit Craters

The oldest exposed lavas of the Kilauea series make up the walls of the craters. They are almost exclusively pahoehoe flows with a maximum thickness of about 30 feet, but aa flows occur in several of the pit craters. There are a few dikes and irregular intrusive bodies. A thin fragmental bed, the Uwekahuna ash, is exposed for a distance of 3000 feet along the northwest edge of the floor of Kilauea, but no other interbedded ash deposits are exposed in Kilauea or in the pit craters.

The lavas of the walls of Kilauea are in general medium to dark gray, vesicular, aphanitic rocks. The lower parts of the thicker flows are nonvesicular and in general lighter in color than the vesicular lavas. Nearly all the lavas have recognizable phenocrysts of feldspar and olivine, but olivine is not abundant.

In thin sections of these lavas olivine appears only as small, sparse phenocrysts. Plagioclase feldspar having the composition of a calcic labradorite (average $Ab_{35}An_{65}$) forms microphenocrysts in nearly all specimens, and brownish augite in several. The groundmasses consist of calcic labradorite, augite, magnetite, ilmenite, and glass. The texture of the nearly holocrystalline specimens from the centers of the thicker flows is intergranular or intersertal. Augite forms elongated, ragged grains between the diverging laths of feldspar; iron ore occurs either in shapeless grains accompanying the augite and feldspar or, more commonly, as crystal growths in the brownish primary glass, to which it gives a black, opaque appearance. Very glassy specimens have a black groundmass containing faint, feathery microlites of feldspar.

A phaneric specimen from the cliff at Uwekahuna was measured by the Rosiwal method. The specimen is a nonvesicular rock with an irregular variation in texture; parts are medium-gray and aphanitic except for some specks of feldspar; other parts are grayish-brown, porous, and crystalline. Sparse phenocrysts of olivine have a maximum diameter of 2 millimeters. Under the microscope the rock was found to consist of augite, calcic labra-

dorite (about $Ab_{35}An_{65}$), iron ores (mostly magnetite), and a few small patches of glass.

The result of the measurement expressed in weight percentages is:

Olivine	1.1	
Augite	54.2	
Labradorite	31.3	
Iron ores	12.6	
Glass	0.8	
	100.0	
Computed sp. gr.	3.07	
Measured sp. gr.	2.9	(The rock is quite porous.)

Specimens collected by me from the walls of Kilauea are all of labradorite basalts very poor in olivine. Washington found labradorite basalt the most common type in the crater walls but also found a few flows of picrite basalts.

Flows in the walls of the pit craters are similar to those at Kilauea, but one flow in the crater of Makaopuhi deserves special mention. Makaopuhi is a double crater, whose older eastern pit had been partly filled by lava before the deeper western pit fell in and exposed a section through the filling. At the top of this section are four pahoehoe flows with a total thickness of about 20 feet; below the flows is a massive body of lava at least 150 feet thick resting upon the reddened slope of the eastern pit. This massive body is a thick, plano-convex lens, which filled the lower part of the crater. It has good prismatic jointing, which is vertical in the upper part of the fill but in the lower part is perpendicular to the convex base. Light green brochantite coats some of the joint planes.

The rock of this fill is light gray and phaneric with a few small phenocrysts of olivine. It consists of augite, labradorite ($Ab_{40}An_{60}$), iron ores, and olivine with a little brown glass containing fine needles of apatite. The texture is intergranular, but locally there are diabasic clots.

The mineral composition in weight percentages is:

Olivine	1.1
Augite	48.2
Labradorite	35.0
Iron ores	13.2
Glass	2.5
	100.0
Computed sp. gr.	3.07
Measured sp. gr.	3.03

The Older Surface Flows

The only flows of the Kilauea series exposed at most places away from the craters are those at the surface. Some of these correspond in age with the topmost flows of the crater walls, but others are the products of later fissure-eruptions. The only means of dating most of them is their relation to the older surface ashes, but the ashes do not extend far from Kilauea. Only the historic flow can be definitely set apart.

In general appearance the pre-historic surface flows are the same as those of the crater walls. Dark gray, vesicular, aphanitic lavas are most common, but in thicker flows the lava is quite crystalline about three feet below the surface. Many of the lavas have feldspar phenocrysts as much as 2 millimeters long, and a few flows are moderately rich in olivine.

Thin sections of these lavas all contain some olivine, but in most sections the olivine grains are small and scattered. The flow of Puu-kole and the big aa flow at the foot of the Hilina pali, however, are fairly rich in olivine. Several specimens have the elongated, rod-like olivine phenocrysts described by E. S. Dana (11, pp 324, 326). The plagioclase feldspar is a labradorite at least as calcic as $Ab_{40}An_{60}$, and in a few sections the phenocrysts are sodic bytownite. Both feldspar and augite occur in two generations.

The groundmasses of most of these lavas consist of feldspar and augite in a black, glassy matrix. The feldspar is in the usual lath-shaped crystals with irregular orientation, and the augite is in anhedral grains accompanying the feldspar and showing a preference for growing along or around it. Under a high powered objective the opaque matrix or base is resolved into a clear brown glass full of beautiful crystalline growths of magnetite and possibly ilmenite. The magnetite is in sharp octahedra arranged in branching lines. All the octahedra in a line have one crystallographic axis in common, and the various lines are parallel to the isometric axes. Exactly similar crystallites of magnetite in basalts from Nevada were described and figured by Zirkel (42). In more nearly holocrystalline specimens the ores are not confined to the glassy mesostasis but are distributed through the rock, partly in parallel rods.

A compact, nearly holocrystalline specimen from near the base of a 20-foot flow was measured by the Rosiwal method. The section consists of a few olivine phenocrysts in a diabasic groundmass of augite, labradorite, iron ores, and some brown glass. The proportions are expressed in weight percentages.

Olivine	6.7
Augite	44.1
Labradorite	28.0
Iron ores	15.1
Glass	6.1
	100.0
Computed sp. gr.	3.25
Measured sp. gr.	2.91

The Historic Flows

The historic flows of the Kilauea series include flows from fissures along the northeast and southwest rift lines and flows from Halemaumau. Flows were erupted along the rift lines in 1823, 1840, 1868, 1920, 1922, and 1923; in Kilauea Iki in 1832 and 1868; and in Keanakakoi in 1877.

The flow of 1823 (the Keaiwa flow) came from the southern half of a fissure eleven miles long southwest of Kilauea (35, 37). The lava is a dark gray, vesicular basalt with recognizable phenocrysts of feldspar and olivine. Augite microphenocrysts are also seen under the microscope.

In 1840 lava broke out at several places in the neighborhood of Makaopuhi, but the greatest outburst was the Nanawale flow in eastern Puna. The lava of this flow has been described by Cross and Washington and analyzed by Steiger. It differs from most other flows of Kilauea in being highly chrysophyric. The groundmass consists in order of abundance of augite, highly calcic labradorite, magnetite, and glass (Cross).

The lava of 1868 reached the surface southwest of Kilauea in four little patches, of which the largest is only 1,000 feet long and the others are much smaller. It is of the common type of Kilauean lava consisting of phenocrysts of olivine, labradorite, and augite in an opaque black base.

The eruption of 1920 is described in great detail in the Monthly Bulletins of the Hawaiian Volcano Observatory for that year (21, 22). A lava dome, Mauna Iki, about 125 feet high was built in the Kau desert southwest of Kilauea, lava flows extending for more than six miles off to the south. Both aa and pahoehoe lava were formed. Specimens of each variety have been analyzed by Washington; they are of the common type of labradorite basalt poor in olivine.

In 1922 a small flow broke out of a fissure in the wall of the western pit of Makaopuhi and covered the bottom of the crater with a jagged mass of aa and rough pahoehoe. Small flows also appeared at Napau crater. Again in 1923 lava appeared near Makaopuhi. All these lavas are of the common type, as are also the historic flows of Kilauea Iki and Keanakakoi.

The floor of Kilauea crater at the present time is almost entirely cov-

ered by the flows of 1919 and 1921, which were formed by overflows of Halemaumau. Older lava, probably of 1894, is exposed in places and has been analyzed by Ferguson.[4] Many other historic flows are exposed in the walls of Halemaumau. The flow of 1919 has a few comparatively large phenocrysts of olivine and smaller ones of augite and labradorite ($Ab_{42}An_{58}$ or more calcic).

Intrusive Bodies in the Kilauea Series

A few small dikes and irregular intrustive bodies occur in the walls of the craters and are especially prominent in Halemaumau. The rock of the dikes is in general dark gray to black, aphanitic basalt, and an analysis by Washington of a specimen from a dike in the north wall of Kilauea showed that the chemical composition of the dike rock is the same as that of many flows. The only analysis of one of the larger intrustives can also be matched among the flows.

A conspicuous body of massive rock in the wall of Kilauea northeast of the Uwekahuna fault terraces was examined by Daly (9, pp. 291-292; 10, pp. 115-116) and considered a laccolith, but Daly's conclusion has not been generally accepted. Most geologists have followed Powers (32, p. 33) in believing that the massive rock is the filling of a former lava tube. The body can be more readily examined now that the flow of 1919 has raised the floor of the crater, and small avalanches have cut into the wall.

The "laccolith" consists of two plano-convex lenses placed end to end with their flat sides down and at nearly the same level, having a total length of about 750 feet and a maximum thickness of 40 feet. (See Pl. I, *A*.) The mass lies with very slight disconformities on 10 to 15 feet of peculiar red, scoriaceous lava flows averaging 2 inches to 6 inches thick but including a few flows 1 foot or more thick. Above the lenses of massive rock are more of these thin flows and a few heavy flows, which arch up over the north end of the northern lens. The remaining height of the 450-foot cliff consists of massive, horizontal flows. Landslides have cut into the south end of the lens about 40 feet and show the base dipping 5° into the wall. Other landslides have broken the surface connection between the two lenses. The flows both above and below the lenses are somewhat brecciated; small apophyses cut the overlying rock; and there are irregular patches of what appears to be intrusive rock in the underlying flows between the two lenses. A two-foot dike of material like that of the main body cuts the underlying flows and the southern end of the northern lens. The top of the massive rock is non-vesicular, and the base has a chilled margin and

[4] All the reliable analyses of Kilauean lavas are listed by Washington (38, pp. 342-352).

upright tubular vesicles. The back wall of the northern lens where exposed is nearly vertical.

The intrusive relations at the base of the "laccolith" are opposed to the lava-tube theory, and it seems probable that the body may be an irregular intrusive injected under thin cover near a lava lake. The intrusive bodies in Halemaumau are examples of masses of this origin. The thin, scoriaceous flows associated with the massive lenses were probably formed by thin, hot overflows from a lake.

The rock of the Uwekahuna intrusive body is a gray, crystalline, gabbroid rock, very rich in olivine. The mineral composition calculated from the chemical composition and a micrometric measurement is given by Daly (9, p. 293) as:

Olivine	40.0
Augite	31.0
Labradorite (Ab_2An_3)	27.0
Magnetite and Ilmenite	1.7
Apatite	0.3
	100.0
Sp. gr.	3.00

Ejected Blocks

The floor of the crater around Halemaumau is thickly strewn with rock fragments of all sizes thrown from the pit during the explosive eruption of May, 1924. On the surface of the "sand-spit," bowlders of an earlier eruption—that of 1790—are mingled with the more recent ones, and bowlders are found in all the ash deposits near Kilauea. Petrographic descriptions of the ejected blocks are given here for comparison with the lava flows; the ash deposits as a whole are described as pages 23-27.

The ejected blocks are entirely of basaltic composition. A great many are of rock types like the recent lavas; others are red, vesicular lava, which is probably old talus or crag material from the former lava lake; but there are many blocks quite unlike the surface flows. Specimens from the ejected blocks of the older eruptions have been described by Dana, Daly, Cross, and Washington. The thin sections here described are from the blocks of the eruption of 1924.

A common and conspicuous variety among the ejected blocks is a light gray, vesicular rock with large phenocrysts of glassy, yellowish green olivine in an aphanitic groundmass. As commonly true of Hawaiian lavas, the vesicles are miarolitic cavities containing fine acicular crystals and thin tables of feldspar. Olivine makes up 23 per cent by volume of the rock. The texture of the groundmass is unusual and consists of small laths of

feldspar, partly in sheaf-like groups, surrrounded by grains of augite, which is extraordinarily abundant. Iron ore is distributed through phenocrysts and groundmass in irregular grains. A somewhat similar texture was found by Washington (38, p. 344) in one of the older blocks.

Another olivine-rich specimen was selected for measurement by the Rosiwal method. It has large phenocrysts of olivine in an intergranular groundmass of augite, labradorite ($Ab_{35}An_{65}$), iron ores, and a little glass. The olivine is full of tiny rods or spindles of a faint purple color, arranged at right angles to the elongation of the olivine. The mineral percentages by weight are:

Olivine	31.8
Augite	38.9
Labradorite	23.4
Iron ore	3.8
Glass	2.1
	100.0

This composition corresponds with a specific gravity of 3.2 compared with the measured specific gravity of 3.04, but the rock is vesicular and porous.

Two specimens of rock rich in olivine also contained hypersthene. In one specimen the hypersthene forms rounded phenocrysts. The other specimen, which is of a rock with perfect platy jointing, probably from the large intrusive body in the wall of Halemaumau, contains large poikilitic anhedra of hypersthene inclosing feldspar laths and a little olivine, measurement of which gave the following mineral composition in weight percentages:

Olivine	19.0
Hypersthene	5.9
Augite	45.1
Labradorite	22.1
Iron ore	6.6
Glass	1.3
	100.0
Computed sp. gr.	3.2
Measured sp. gr.	3.09

Another rock type differing from the ordinary flows of the Kilauea series is light-colored, dense, aphanitic labradorite basalt with a very little olivine. A specimen of a light brownish gray rock has a few small olivine phenocrysts and a few specks of feldspar, which the microscope shows to be groups of labradorite laths ($Ab_{30}An_{70}$), in an intersertal groundmass of augite, labradorite, and iron ores.

The vesicles in many of the ejected blocks are true miaroles lined by projecting crystals. Feldspar, augite, ilmenite, and magnetite can be recognized with a hand lens. In several specimens of the ejected blocks and also in specimens from the Uwekahuna "laccolith" many of the vesicles contain little, round, white crystals about 0.2 millimeters across, which were noticed by Dana (11, pp. 327-328) and Washington (38, p. 340) and considered a zeolite. Upon examination with a binocular microscope, nearly all these were found to be complexly twinned, but some have faces of either octahedra or dodecahedra, and many have hexagonal outlines. The mineral was examined by the immersion method and found to have very low birefringence, an irregular mottled appearance between crossed nicols, and an index of refraction very nearly 1.485. These optical properties indicate either analcite or cristobalite. The mineral was infusible before the blowpipe, gave no sodium flame, and was not fusible with hydrocholoric acid. Mr. J. F. Schairer kindly tested a small amount of the mineral weighing about 8 milligrams and found 75 per cent of silica. The impurity is probably due to small fragments of feldspar and ilmenite attached to the crystals. The mineral, therefore, is quite surely cristobalite.

Cristobalite was definitely identified by Cross (8, p. 11) in an olivine-plagioclase basalt from Olokele Canyon, Kauai. It occurs in vesicles as minute, dull-white rhombic dodecahedra about 0.3 to 0.5 millimeter in diameter, and has the same optical properties as in the rocks of Kilauea.

A few of the ejected blocks are slightly altered. The olivine phenocrysts in one specimen contain a red substance, in places in regular, branching patterns, and in other places so abundant that the olivine is opaque. The augite is somewhat discolored, but the feldspar is perfectly fresh. In the same specimen the vesicles are lined by a pale blue coating, which under the microscope is a cryptocrystalline aggregate with moderately high birefringence. The same substance fills some of the interstitial spaces in the groundmass and has possibly replaced primary glass.

Some of the more coarse grained blocks crumble easily, probably as a result of having been reheated. Many of the bowlders ejected in 1924 were incandescent.

Ejected blocks are also found around the pit crater of Alealea (Alae) and along the source fissure of the flow of 1823 in Kau . Two specimens from Kau were studied in thin sections. One is a light gray, nonvesicular phaneric rock, a typical basalt with a few small olivine phenocrysts. Some of the iron ore is in rods or plates having a perfect parallel arrangement. The other specimen is an aphanitic, vesicular rock of an unusual light brown color. It has a few rounded microphenocrysts of olivine in a very fine grained, hypocrystalline groundmass.

Most of the blocks are plainly from lava flows of the Kilauea series, but some of the fine grained, light colored ones may be from the pre-Kilauea series, which underlies the volcano. The common occurrence of course, chrysophyric rocks similar to that of the Uwekahuna intrusive body suggests that the throat of the volcano may be bordered by numerous intrusives like those in the walls of Halemaumau.

GENERAL PETROGRAPHY OF KILAUEA

The lavas of Kilauea are basalts or picrite basalts with possibly some basaltic andesites in the pre-Kilauea series. Some of Noble's specimens of pre-Pahala flows were classified as andesites by Cross (38, p. 120). But an analysis of the predominant lava type of the pre-Pahala corresponds to a basalt, and specimens collected by me from the pre-Kilauea are also basalts. None of the analyzed rocks of Mauna Loa or Kilauea is an andesite. Labradorite basalt, mostly with about one per cent of olivine is by far the most abundant variety, but there are some olivine basalts, and a few flows. Many of the gabbroid explosion blocks are picrite basalts containing 15 to 40 per cent of olivine.

Only a few minerals and those of a rather constant character enter into the composition of the lavas. Olivine is present as phenocrysts in nearly every specimen. It incloses small crystals of magnetite and round blebs of glass. The interference figure shown by sections perpendicular to an optic axis is nearly a straight bar, indicating an optic axial angle near 90°, which corresponds with a content of ferrous oxide of about 12 per cent. An analysis by Steiger (9, p. 295) of olivine from the Mauna Loa flow of 1852 gave 11.44 per cent of ferrous oxide.

Pale brownish augite is the most abundant mineral, making up as much as 54 per cent of the rock. Small augite phenocrysts, though sparse and mostly poorly formed, can be found in many specimens. Most of the augite occurs as irregular grains in the groundmass. Its optic angle as determined roughly in thin sections seems to be a little less than the normal angle (58-60°). An augite from Haleakala, Maui was analyzed and described by Washington and Merwin (39). According to their interpretation it is essentially hedenbergite-diopside with small amounts of acmite, clinoenstatite, and alumina in solid solution. It contains 1.89 per cent of titania and has an optic angle of 61-62° for red light and of 58-60° for blue light.

Hypersthene of a weakly pleochroic variety was found in only two specimens, both of blocks ejected from Halemaumau, but hypersthene has been found by Cross in some of the pre-Pahala flows of Mauna Loa. In one of

my specimens the hypersthene occurs as rounded phenocrysts and in the other it forms ragged ophitic plates inclosing laths of labradorite.

Plagioclase feldspar in all specimens is a calcic variety, mostly a calcic labradorite with a composition near Ab_1An_2, but in a few specimens the phenocrysts are a sodic bytownite. Feldspar phenocrysts are practically universal.

Magnetite and ilmenite appear in all specimens, usually as late products of crystallization. The magnetite forms beautiful crystallites in some glassy lavas.

Brown glass is the only other common constituent. In a few nearly holocrystalline specimens it is full of tiny needles, probably of spatite. The glassy residue in many flows is opaque with iron ores.

Cristobalite, recorded for the first time from the island of Hawaii, occurs in the vesicles of some of the coarser rocks.

Sulphur and various sulphates have been formed in places by fumarolic action.

The texture of the more completely crystallized lavas ranges from intersertal to diabasic, but the common material from thin flows or the tops of the thick flows has a black, glassy base.

THE EJECTED PRODUCTS

CLASSIFICATION

The materials ejected by Hawaiian volcanoes may be classified as rock fragments, ashes, bombs, and scoriae. Rock fragments are angular pieces of rock shattered by explosions, and range in size from those 2 millimeters in diameter to those with a greatest dimension of 3 or 4 meters. They may be classified according to size after the following scheme, which is slightly modified from Wentworth (40).[5]

Maximum Size	Minimum Size	
....	256 mm.	Bowlders or blocks
256 mm.	64 mm.	Cobbles
64 mm.	4 mm.	Pebbles
4 mm.	2 mm.	Lapilli

Volcanic ash includes all fragments of rocks, minerals, and glass less than 2 millimeters in diameter. The finest material may be called "dust." The term "ash" is also used in this paper in a general sense as including all bedded volcanic ejecta. The term "bomb" is restricted here to objects consisting in part at least of lava ejected in a liquid or semiliquid condition. As shown by Perret (30), the usual type of Kilauean bomb is a rock fragment with a coating of lava.

Scoriae are cindery lava particles of varying size, which were ejected in a molten condition. It is not always possible to tell whether scoriae were formed contemporaneously with the explosion or whether they are older. Unusual glassy ejecta at Kilauea are Pele's hair, glass droplets or Pele's tears, and thread-lace scoriae.

ASHES IN THE PRE-KILAUEA SERIES

Several beds of fine grained yellow or reddish-yellow stratified ash are interbedded with the lavas of the pre-Kilauea series and exposed with them in the cliffs of southern Puna and Kau. The thickest beds observed are between 15 and 20 feet thick but pinch and swell abruptly. Five beds can be seen in the seaward face of Puu Kapukapu; but, because of the dis-

[5] Wentworth would restrict the terms "bowlder," "cobble," and "pebble" to rounded rock particles. In speaking of angular particles "block" may be substituted for "bowlder," but there seems to be no words in the English language to designate angular stones of the size of cobbles and pebbles. Until such terms are proposed and accepted, "bowlder," "cobble," and "pebble" must be used in a more general sense.

continuity of the beds, there is no close agreement in the sections in different places, although the greater part of the ash is everywhere in the upper part of the cliffs.

These beds agree in character and thickness with the pre-Pahala ashes of the Mauna Loa slope as described by Noble (28, p. 119). The ashes in rainy sections of Mauna Loa are decomposed, locally to clays, but the beds in the arid country south of Kilauea are quite fresh.

THE PAHALA ASH

Several areas along the Mauna Loa slope north and northwest of Kilauea are covered by deep soil and contrast sharply with the usual thinly-covered lava flows. One small area of this kind is on the small pali north of the Keauhou Ranch, another is the Bird Park kipuka, and there are several others, for instance those near the Kapapala Ranch gate. Such kipukas are made especially noticeable by the more luxuriant growth of vegetation on them. The sugar plantations around Pahala are supported by soil-covered areas of this kind.

The Pahala soil, first mentioned by Dutton (12, pp. 97-98), was considered by him an alluvial deposit formed on plains near sea-level. In 1887 Hitchcock (18, p. 55) advanced the theory that the soil was a decomposed volcanic ash, and later workers have accepted this interpretation. The ordinary surface material of the Pahala ash is a light, loose, ocher-yellow soil, similar in appearance to very fine sawdust. Hithcock says (17, p. 153) that the natives used to amuse themselves by jumping into banks of the ash just as children jump into snowdrifts. The loose surface soil, entirely fine grained and giving no convincing proof of its origin is in deeper exposures unmistakably volcanic ash. In the dry stream channel near the northernmost tank on the Peter Lee Road the following section is exposed:

	Feet
Loose, ocher-yellow ash	13
Stratified, indurated, gray ash	15
Base not exposed	

The yellow ash layer contains several thin bands of fine lapilli and gray ash and is pisolitic near the base. The lower layer consists of thin beds of gray ash (some of it pisolitic) and lapilli. It is sufficiently indurated to form blocks in the stream bed.

Examination of specimens of the Pahala ash with the microscope shows that it consists of fragments of yellow glass and a smaller amount of mineral fragments. Many of the glass fragments were derived from vesicular material.

The thickest section found is in the scarp back of the Kapapala half-way house, where about 95 feet of ash is exposed in a steep-sided gulch. The apparent thickness of this section may be in small part due to normal faults of slight displacement such as are exposed at nearby places. Noble gives the maximum thickness of the Pahala ash as 75 feet.

A number of exposures show plainly that the Pahala ash along the Mauna Loa slope is the product of two or more eruptions. In the section on Peter Lee Road is a sharp division between the two parts, the lower layer having a thin, reddened zone at its top. At some neighboring localities the yellow layer alone is exposed and is underlain by an aa flow, which must be intercalated between the two layers. In a short valley just north of the Kau-Volcano road at an elevation of 2570 feet the following section is exposed:

	Feet
Loose, yellow ash	15
Well bedded ash, mostly gray	15
Slight unconformity	
Light yellow ash, contains pebbles and seems to be reworked	2
Thin bedded, yellow and gray ash	4
Base not exposed.	

At several places lava flows are interbedded with the ashes. There are also deposits of yellow ash in southeastern Kau. The flat-topped hill, Puu Kaone (Sand Hill), is covered by yellow soil, which must be very fertile, for grass continues to grow upon it in spite of the lack of rain and the large number of goats that pasture upon it. A small gully exposes 45 feet of ash made up of alternating yellow and gray ash. The yellow ash is fine grained but contains many lapilli and small pebbles; the gray ash, which is coarser, is in beds as much as 1 foot thick, and makes up about one-third of the section. Puu Kapukapu is a prominent hill capped by 20 feet of yellow ash, and there is also a patch of ash on the Kulalauula pali. At least 60 feet of thin bedded, yellow and gray ash like that of Puu Kaone is exposed in a straight-sided landslide cirque southwest of the Keana Bihopa Kipuka. The same thick bed is exposed in several places in the Hilina pali at the top of the pre-Kilauea series.

Because of its lithologic likeness and similar stratigraphic position the yellow ash of eastern Kau is correlated with the Pahala ash of the Mauna Loa slope. Excavations on the Hilo-Volcano road near Glenwood expose about 10 feet of red clayey material, which is apparently much weathered ash. The deposit is unstratified except for thin carbonaceous streaks. The red color and clayey texture are believed to be due to weathering under lateritic conditions. (The annual rainfall at Glenwood is 228 inches.) The upper part of the Pahala ash is red when freshly exposed in the rainy forest

north of Kilauea, but when allowed to dry a short time in the sun, it takes on its characteristic ocher-yellow color. The Glenwood ash is here correlated with the Pahala ash.

In addition to the deposits in Kau and along the Volcano Road, yellow ash is found all the way to Ka Lae, the south point of Hawaii, and up Mauna Loa to an elevation of 7,500 feet. Ash deposits are also found in other parts of Hawaii, especially along the Hilo and Hamakua coasts, where they support large sugar plantations, but where there is no evidence that the deposits had a common source with the yellow ashes of Kau. Within the Pahala ash itself are breaks but no complete changes in size or character of material, so that it is justifiable to assume that it came from a single source or at least from closely related sources. Several possible sources have been mentioned.

Emerson (14, p. 435) suggested that the so-called "caldera" of Mohokea was a logical source, inasmuch as it lies in the midst of the region where the ash abounds. Recent work, however, has shown that Mohokea is not a crater but only a great valley formed by faulting and erosion.

Hitchcock regarded Mokuaweoweo, the summit crater of Mauna Loa, as the most probable source for the Pahala ash because he had noted ash deposits, which he considered equivalent, at various localities all around Mauna Loa. The absence of the deposit around the summit crater he explained by the assumption that the ash was carried so far into the air and the force of the eruption was so great that no ash fell near the source. This reasoning is proved false by the proximity to Kilauea of the ashes from its eruptions. No ash beds occur in the walls of Mokuaweoweo, so that were Mauna Loa the source of the yellow ash, the summit of Mauna Loa must be post-Pahala. In another connection Hitchcock (17, p. 148) suggests that Puu o Keokeo on the southwest flank of Mauna Loa may have been the source of the Pahala ash, but the text does not make clear whether the suggestion is to be regarded as the author's own or that of Dr. S. E. Bishop.

The summit cones of Mauna Kea have been often cited as evidence that that volcano closed its active history with great explosive ash eruptions. If this view is correct, Mauna Kea might be considered as the main source of the Hawaiian ash deposits. But examination of these cones shows that they are not ash cones, as has often been supposed, but cinder cones quite like those at the sources of many Mauna Loa flows. It is true, however, that the eruptions of Mauna Kea were more explosive than those of Mauna Loa, for they built bigger cones and produced many more bombs and some beds of ash. The headward gullies of the Wailuku River and other dry stream channels expose a few ash beds as much as 10 or 15 feet thick inter-

bedded with the uppermost lava flows, but there is no great surface mantle of ash as there would be if Mauna Kea were the source of the ashes of the whole island. Many of the cones of Mauna Kea are above the trade wind zone, as was pointed out to me by Finch, so that the great amounts of ash in Kau cannot be explained by wind transportation from Mauna Kea. It is hardly conceivable that lapilli could have been blown from Mauna Kea to Puu Kaone. E. D. Baldwin (3) suggested that

> . . . . . at some ancient period there has been a great line of yellow eruptions, extending from Puu Kapukapu . . . . past the Kamakaia hills to the lower portion of Kau, and that the sources of this yellow eruption in the lower part of Kau have been covered up with later flows . . . . and that the great beds of yellow soil that we find today all over Kau were blown there from these sources.

The cones whose yellow "tufa" reminded Baldwin of the Pahala ash are, however, cinder or lava cones, and show no evidence of having produced ash.

Is it possible that Kilauea was the source of the Pahala ash? Emerson (14) suggested this idea only to reject it as "extremely improbable." Nevertheless, there is considerable evidence in its favor. With the exception of the Pahala ash, the thickest deposit of ash known on Hawaii is at Kilauea, so there is no questioning the potency of Kilauea as an ash-producer. Moreover the distribution of the Pahala ash is exactly what would be expected if Kilauea were its source and the trade winds the transporting agent. It is similar to the distribution of the Kilauean ashes. Baldwin pointed out that the distribution agreed with his theory of a source in the region of the Kamakaia Hills, but it agrees even better with the theory that Kilauea was the source; for the greatest thickness found is north of Kamakaia. The miscroscopic character of the Pahala ash is the same as that of the older Kilauean deposits. The ash at Puu Kaone is somewhat coarser than that near Pahala; this condition can be explained if Kilauea were the source, but not if the material came from Mauna Loa or Mauna Kea. The Glenwood ash, now so thoroughly decomposed, was probably fine grained, as would be expected on the windward side of the source. The source of the Pahala ash can be determined finally only by a study of the ash deposits of the whole island.

ASHES OF KILAUEA CRATER

THE UWEKAHUNA ASH

The only ash bed in the walls of Kilauea is exposed at the base of the Uwekahuna cliff northeast of the fault terraces. Another ash section was formerly exposed southwest of the fault terraces (31, p. 230) but was buried by the lava flow of 1919 from Halemaumau. A careful examination

of the walls showed no other beds, but ash layers only a few inches thick might escape observation.

The exposed ash bed extends along the base of the cliff for about 3,000 feet from the niche at the northeast end of the fault terraces to the point where it dips below the level of the crater floor. At the northeast end of the exposure the bed is three feet thick and consists of gravel, a few lava-coated bombs, and rock fragments commonly 6 or 8 inches across but reaching a maximum size of about 16 inches. Beneath the Uwekahuna intrusive body is 6½ feet of ash having a basal layer of medium-coarse black ash overlain by 2 feet of gravel and cobbles, then another ash layer overlain by a second gravel stratum, and at the top about 8 inches of yellow ash with glass droplets and crushed thread-lace scoriae (11, pp. 163-166). At the southwest end of the exposure the ash bed lies on the surface of an unconformity in the lavas.

According to Powers, the incomplete section formerly exposed at the other locality was 17 feet thick and was composed of yellow ash containing rock fragments 1 or 2 inches across.

The Older Surface Ashes

The surface around Kilauea is covered by a deposit of volcanic ash, which is thick enough to be noticeable (at least 1 inch) on the Hilo road six miles south of Kilauea, beneath the Keiwa flow along the Great Crack sixteen miles southwest of the volcano, and on the Mauna Loa slope in Ohaikea four miles to the west. The ash deposits have a maximum thickness of 35 feet in the cliffs forming the southeast rim of Kilauea crater. The thicknesses at other places around the crater are: 4½ feet on the top of Uwekahuna, 4½ to 6 feet at the Observatory, 2 to 3½ feet on the road east of Kilauea Iki, and 13½ feet on the northwest rim of Keanakakoi. (See fig. 3.) The floor of the crater is covered by recent flows so that the only ash on its surface is that of the explosions of 1924. The ash deposits vary from place to place not only in thickness but also in the proportions and coarseness of the different materials of which they consist.

A bed of the remarkable light pumice, known to the Hawaiians as "limu" (moss) and called "thread-lace scoria" by Dana, forms a conspicuous basal layer of the ash deposits around the northern rim of the crater, where sections were especially well exposed during the summer of 1925 by work on the roads. "Thread-lace scoria" is a very expressive name for a light greenish-yellow froth of basaltic glass, whose vesicle walls are reduced to a skeleton of glass threads so that it can be easily crushed between the fingers. Dana's description leaves little to be added.

The bed of thread-lace scoriae lies directly upon the topmost lava flows nearly everywhere, but along the road between the Volcano House and Kilauea Iki a thin, discontinuous bed of purplish-gray, clayey ash underlies it locally. The scoria bed itself reaches a thickness of 2½ feet in pockets but is less than 1 foot thick in most places. Figure 4 shows two areas of greater thickness, one north of Kilauea Iki and a larger one north of the main crater. Had Kilauea Iki been the source, there should be thick deposits of scoriae on

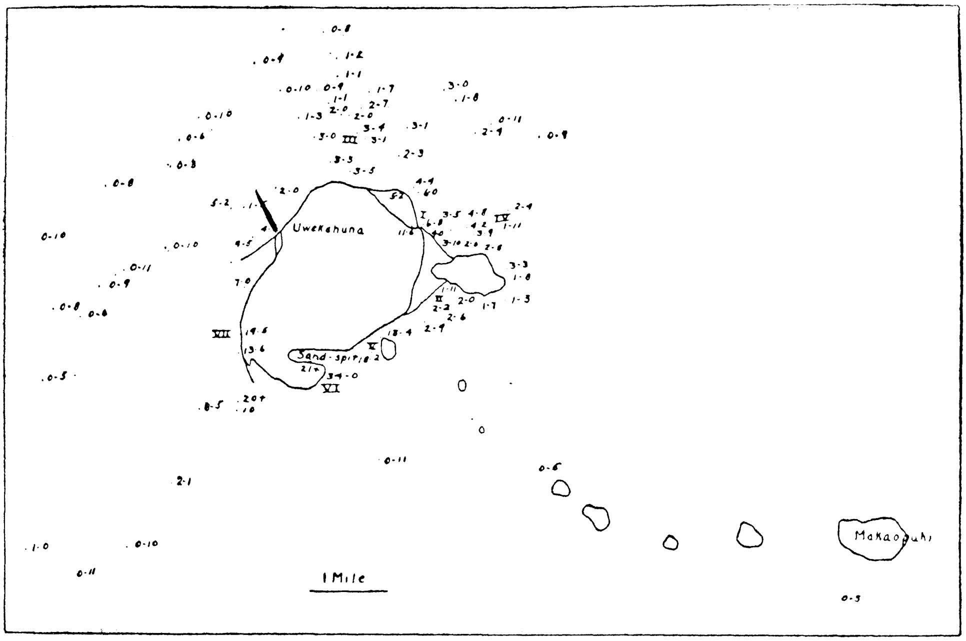

FIGURE 3. Map showing the distribution of the surface ashes of Kilauea. Thicknesses in feet and inches. Roman numerals show the location of the sections given in the text.

its inner walls, none of which was found. The scoriae were evidently produced by fountaining in the main crater, probably in the northern and northeastern portions, during a period of southwesterly, or "Kona" winds. A few days would have been sufficient for the formation of the scoriae.

Thread-lace scoriae, besides occurring in the bed just described, are also found in the Uwekahuna ash and in pockets beneath the ash of 1924 around the southern part of Kilauea crater. The latter deposit locally reaches a thickness of several feet but consists of a coarser variety of scoriae than the basal layer. In the younger material some of the vesicles have complete walls of glass, and many of the scoriae are inclosed in a thin, brown glass

membrane. Identical scoriae occur around many of the Mauna Loa source-cones and also in the Kamakaia cones, but at only a few places does it have the perfection of the scoriae of the basal layer.

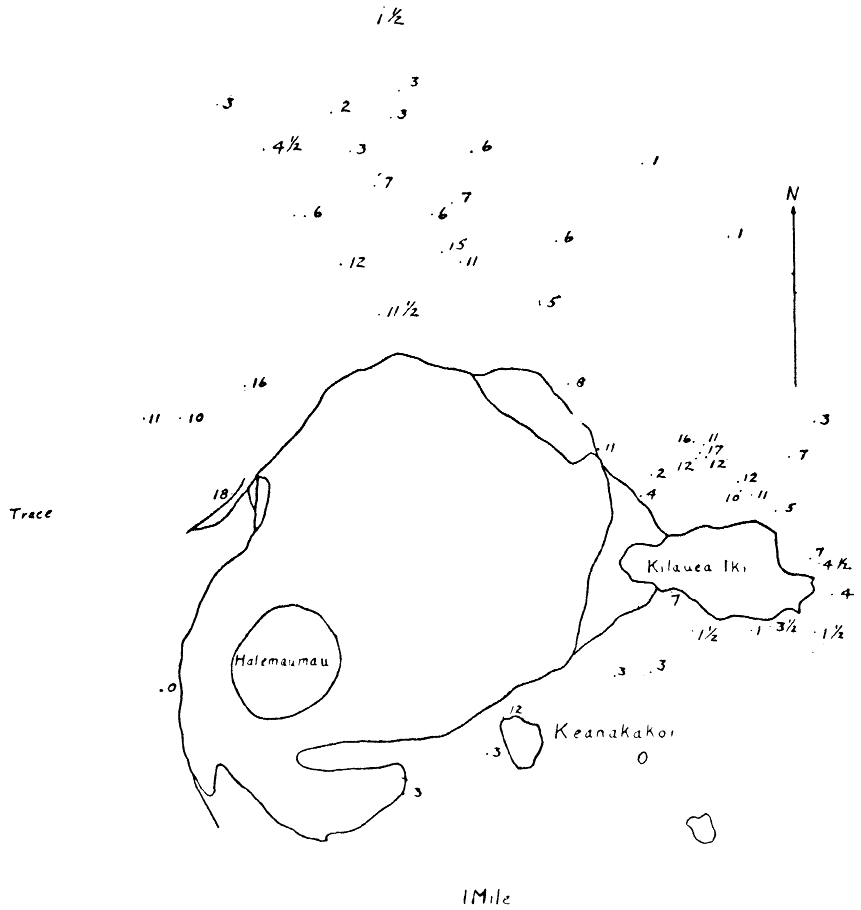

FIGURE 4. Map showing the distribution of the basal layer of thread-lace scoriae around Kilauea. Thicknesses in inches.

Overlying the thread-lace scoriae around the northern end of Kilauea are well bedded ash deposits. Typical sections, whose location is shown in figure 3, are as follows:

I.

	Feet	Inches
Coarse gray ash with pebbles and lapilli	0	9
Tan ash	0	1
Coarse well-bedded dark-gray ash with a few lapilli	0	9
Lapilli	0	0½
Coarse black ash	0	6½
Black to greenish-gray ash	1	1½
Tan ash with red top and thread-lace scoriae at base	0	2
Dark-gray ash	1	8
Thread-lace scoriae	0	11
Clayey gray ash	0	5½
Pahoehoe	....	....
	6	6

II.

	Feet	Inches
Ash with streaks of lapilli and gravelly top	1	4
Yellow ash	0	2½
Gray ash	0	4
Black scoriae	0	1
Gray ash	0	3
Ash with carbonaceous material at top	0	4
Clayey gray ash with red top	0	2
Thread-lace scoriae	0	5
Pahoehoe	....	....
	3	1½

III.

	Feet	Inches
Coarse gray ash with scoriae at base	1	9
Gray, clayey ash	0	4
Thread-lace scoriae	1	3
Fresh pahoehoe	....	....
	3	4

IV.

	Feet	Inches
Ash and lapilli	0	4½
Fine, bedded ash	0	8½
Fine, clayey ash with dark top	0	2½
Thread-lace scoriae	0	7
Pahoehoe	....	....
	1	10½

The ash beds thicken abruptly south of Uwekahuna on the west side of Kilauea and Keanakakoi on the east, but they are strictly equivalent to the ashes north of the crater. Traces of the basal layer of thread-lace scoriae can be found at the base of the ash section in the cliff at the east end of

the flow of 1921, and the deposits are continuously exposed around the rim of the crater. Two sections are:

V.

	Feet	Inches
Bowlder gravel	1	6
Ash, upper part coarse gravel and cobbles, scattered cobbles in lower part	5	10
Black scoriae	0	10
Compact yellow and gray ash	9	9
Crushed thread-lace scoriae	0	3
Pahoehoe	....	....
	18	2

VI

Bowlder gravel	2	0
Bedded yellow ash	9	0
Black scoriae	0	6
Yellow ash	22	0
Thread-lace scoriae	0	3
	33	9

The bowlder gravel, which consists of rock fragments of all sizes up to blocks weighing several tons, and which has a maximum thickness of ten feet in the sand spit near Halemaumau, lies disconformably on the lower beds. Enough fine ash accompanied the bowlder gravel to give it a smooth surface, over which are scattered large bowlders thrown out in the final paroxysms of the eruption. Many of these bowlders are large; a huge one weighing about eight tons lies 6,000 feet southeast of the present pit, and another weighing about two tons was seen just west of the summit of Uwekahuna, a mile north of Halemaumau. Scattered bowlders can be found as far away as the Keauhou Ranch, and lava-coated bombs, some as large as a man's head, are locally mingled with them. Impact pits formed in the fine surface ash by the fall of the larger bowlders and bombs are still preserved. The bowlders either remained in their impact pits or bounced on, many of them breaking on striking the earth.

Good sections of the ashes are exposed along the cracks, which extend southwest from the rim of the crater. A section near the crater is:

VII.

	Feet	Inches
Fine, gray ash of the eruption of 1924	0	5
Coarse thread-lace scoriae, many with black, glassy skins	3	0
Fairly well bedded, gray ash with pebbles	1	8
Pebbles and cobbles	0	8
Brown ash containing pisolites and pebbles	0	6
Coarse gravelly ash	1	3
Disconformity	....	....
Medium coarse, grayish-yellow ash with pisolites	2	0
Very fine, dark brown pisolitic ash	0	11
Grayish-yellow ash	4	10
Coarse black ash	4	2
Pahoehoe	....	....
	19	5

The ash deposit thins abruptly southwestward, five miles from the crater being less than one foot thick. The ash near Mauna Iki is in four layers: (1) a basal layer of compacted, fine, light yellow pisolitic ash, whose surface is sun-cracked; (2) loose, medium, greenish-black ash; (3) compacted, yellowish-gray pisolitic ash; and (4) a scattering of pebbles and thread-lace scoriae. Some of the pisolites in the third layer are three-quarters of an inch across.

The finer ashes examined under the microscope were found to consist of mineral fragments and glass fragments. The glass fragments are parts of glassy scoriae coarser than the thread-lace variety, and some contain stretched vesicles. Some of the fine, light gray ash is more than half mineral fragments, but the black ash and especially the indurated yellow ash of sections No. V and No. VI are more than 75 per cent glass.

The surface ashes, with the exception of those of 1924, were deposited before the earliest written records of Kilauea, but Ellis gives native traditions of an eruption in 1789 or 1790, which killed a number of people (13, pp. 186-187). The story can be found repeated in nearly every account of the volcano. Direct evidence of a most unusual kind proves that there was an eruption witnessed by natives: in the spring of 1920 R. H. Finch discovered fossil human footprints in the pisolitic ash of the Kau desert. Other footprints have since been found in surprising numbers at many places along the route of the ancient trail to Uwekahuna (23, pp. 114-118, 156-157). Unmistakable footprints are found in both the upper and the lower pisolitic layers, so that they were unquestionably formed during the mud-rains that deposited the ash. (See Pl. I, *B*.) The surface ash near Kilauea was gravelly and unsuited to retain the impressions.

Dana considered the surface ash as the product of the eruption of 1790, but Hitchcock thought it improbable that all the ash was of one age, and

Powers (31, p. 232) mentioned the disconformity beneath the gravelly ash near Halemaumau, which proves that there were at least two eruptions. In the present paper the coarse upper layers of ash all around the crater together with the coarse gravel near Halemaumau and the footprint layers of the Kau desert are considered to be products of the eruption of 1790.

The ashes older than 1790 are not, however, the products of one eruption. The ash sections around the northeastern part of the crater show black, carbonaceous layers mostly about half an inch thick and contain remains and impressions of ferns and other plants. The ash immediately below these soil layers (for such they are) is reddened in places. The soil layers are somewhat discontinuous, though four intervals between eruptions are shown quite definitely. The basal member of the ash series is a thin layer of gray, clayey ash, which occurs only locally and whose existence as a separate unit is doubtful. Next above the gray clay comes the layer of thread-lace scoriae and a small amount of associated ash, which is the basal layer in most places. Between the thread-lace scoriae and the coarse ash of 1790 are two thin ash deposits separated by a soil layer, and another soil layer overlies the upper one. Including the ash of 1790 there is thus evidence of four and possibly five periods of explosive eruption in prehistoric times. It is probable that there were more eruptions which, like the eruption of 1924, left no trace around the windward side of the crater.

The yellow tuff along the southern rim of the crater corresponds to the ash of the two eruptions next preceding 1790, for traces of thread-lace scoriae occur at its base, and the ash of 1790 overlies it. The lee side of the crater, however, is a desert, so that no plants grow to mark the intervals; and it cannot be determined how much of the ash is due to any one eruption or whether there were several eruptions. There is some evidence that the layer of black scoriae in sections No. V and No. VI (p. 32) occurs at or near the top of the lower deposit.

An ash bed at least three feet thick shown in an open fissure near Cone Peak is separated from the surface ash by 12 feet of lava flow, which seems to be a flow from Cone Peak. No other ash sections could be found in neighboring fissures, but the field relations suggest at least that the Cone Peak lava flow occurred during the period of explosive eruptions.

The age in years of the ash beds older than those of 1790 can only be estimated roughly. The lava flows below the ash are fresh, and the soil layers between the different deposits are thinner than the post-1790 layer at the surface. The establishment of a forest, which has taken place entirely since the lava flow on which the ash lies, is apparently not yet complete, for all the trees are young, and old inhabitants have noticed an advance of the forest within the last 30 years. The largest tree I saw near Kilauea was

a five-foot koa near the Hilo road at an elevation of 3,800 feet. Dr. F. B. H. Brown of the Bernice P. Bishop Museum estimated from data furnished by me that the tree was between 150 and 300 years old, probably nearer 300. This tree is quite surely older than the ash of 1790. The age of the oldest ash is probably not over 300 to 500 years.

THE ASH OF 1924

Kilauea was erupting explosively from May 10 to May 24, 1924 (26), and during this period threw fragmental material over a large area. The amount of ash ejected was far less than in 1790 for the maximum thickness of the ash of 1924 is about 1½ feet compared with more than 10 feet in 1790. The floor of the crater for at least 1,000 feet from the pit is thickly covered by angular rocks. The largest lies near the east rim of Halemaumau, is 11 feet long, and has an estimated weight of 14 tons. One block weighing 8 tons was thrown 3,500 feet, and several were thrown nearly 5,000 feet. The blocks are nearly all freshly broken and show no sign of fusion although many were incandescent when ejected. Heat cracking may have been partly responsible for the breaking of many of the blocks when they fell. No bombs have been found.

The light gray ash formed by the explosion, fell either as dust or as pisolitic mud rains. Fine dust was carried 25 miles or more to the southwest. Along the southwest rim of the crater the ash is 3 to 5 inches thick. Examination with the microscope showed that the ash consisted almost entirely of mineral fragments and that the few glass fragments were probably pieces of older rocks rather than of fresh lava.

STRUCTURE

THE KILAUEA DOME

Topographically Kilauea is an independent dome on the flank of Mauna Loa, but because of the very gentle slope of both Mauna Loa and Kilauea its dome-like nature is not apparent in some parts of the area. In fact, before the publication of the topographic map, some geologists considered that Kilauea was merely a sink in the side of Mauna Loa. The topographic map shows, however, that the only place where the slope is such that flows from Mauna Loa might reach the crater of Kilauea is a strip somewhat less than one mile wide along the foot of the Mauna Loa slope north of Keauhou Ranch. A flow reaching the Kilauea dome to the west of this strip would be deflected off to the southwest, as was the Keamoku flow; one to the east would flow off to the northeast. As most of the critical slope is covered by the Pahala ash, it is evident that no great amount of recent lava has come down there. Under these conditions it would have been impossible for flows from Mauna Loa to build the Kilauea dome.

Two explanations of the Kilauea dome seem possible: either it has been built up by the volcano itself; or it has been arched up by pressure from below, for instance by a laccolithic intrusion, as Daly (10, pp. 109-11) postulated. Several lines of evidence, however, show that the lavas really came from the vicinity of the present crater:

1. In several kipukas on the flanks of Mauna Loa along the Kau-Volcano road and as close to Kilauea as the Bird Park, there are thick deposits of the Pahala ash interbedded with the Mauna Loa lavas, yet the Pahala ash does not appear at Kilauea either at the surface or in the 450 foot section at Uwekahuna. The flows of the crater walls cannot then have come from Mauna Loa.

2. Many of the long flows of Mauna Loa are aa like the Keamoku flow near Kilauea, but aa flows do not occur in the walls of Kilauea.

3. In the Uwekahuna ash interbedded with the lavas of the crater wall are ejected bowlders 3 or 4 feet across as well as large lava--coated bombs, which obviously came from a near-by source. Therefore, there must have been a volcanic vent in the vicinity of the present Halemaumau before the wall of Uwekahuna was built.

4. On the back slope of Uwekahuna the ropy pahoehoe surfaces indicate a direction of flow to the west, so the slope has not been reversed

by tilting. Because of the heavy cover of ash, exposures are comparatively few.

5. A final bit of evidence is the homology with Mokuaweoweo, the summit crater of Mauna Loa. The similarity in all essentials between Mokuaweoweo and Kilauea is one of the most striking impressions made on an observer, and in the case of Mokuaweoweo there is of course no doubt as to the source of the lavas of its walls.

The Kilauea dome was therefore built up, probably by the co-operation of two processes; overflow from a central lake and fissure eruption. Flows from Halemaumau have built a lava cone in the present crater and in 1921 overflowed the crater wall for a short distance. Fissure eruptions have occurred frequently southwest of the crater. The way the contour lines bend around the eastern end of Kilauea Iki, which is the highest point near Kilauea with the exception of Uwekahuna, suggests that large quantities of lava were extruded there. Road cuts in the vicinity show thin, vesicular flows such as occur close to the sources of some eruptions. The Twin Craters were undoubtedly the source of some lava.

THE KILAUEA-MAUNA LOA CONTACT

The relation of Kilauea to Mauna Loa never has been satisfactorily determined. Dana (11, pp. 260-264) believed at first that Kilauea was younger than Mauna Loa and subsidiary to it, but his later reasoning inclined him to believe it independent and perhaps younger. Dutton (12, pp. 120-121) insisted that Kilauea was an independent volcano, whose lavas had interfingered with those of Mauna Loa. He did not make any statement as to their relative ages. In recent years Jaggar (20, p. 198) has held that Kilauea is much older than Mauna Loa, whereas both Daly (10) and Noble (28, p. 121) have believed that it is only a sink in a platform of Mauna Loa lavas. None of these conclusions, however, was based on detailed field work around Kilauea.

A study of the well-marked topographic boundary between the Mauna Loa and Kilauea domes shows important structural relations. On the northwest the Mauna Loa slope descends in a series of terraces, which were noticed by Dutton and regarded as of alluvial origin and so as evidence of uplift. This interpretation was largely due to Dutton's failure to recognize the Pahala ash as ash. The terraces are plainly abnormal features of the topography that cannot be explained by any vagaries of stream erosion or lava flows but must be either wave cut terraces or fault terraces. As the terraces are covered nearly everywhere by post-Pahala lavas, which have cascaded over them, and as vegetation is fairly heavy, direct observation is difficult. An examination of the topographic map

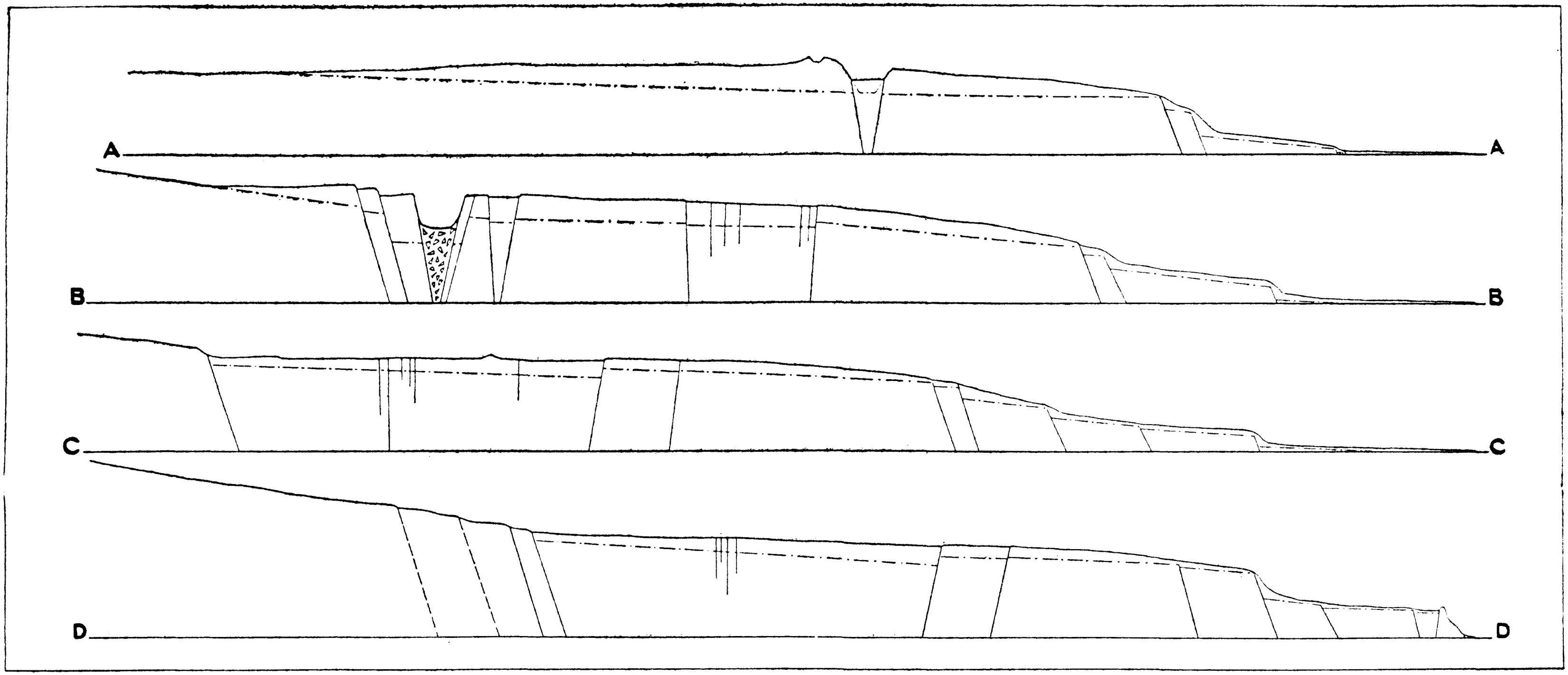

Figure 5. Structure sections across the Kilauea dome. A-A is drawn across the Puna ridge through the crater of Kane Nui o Hamo and the eastern pit of Makaopuhi. A line drawn from the base of the Kilauea series at the north edge of the area to the approximate base of the series in the fault-cliff south of Makaopuhi does not quite pass below the bottom of the western pit of Makaopuhi (not in the line of the section). As the walls of Makaopuhi are entirely made of the Kilauea series, this section shows that the Puna ridge has been built up by flows of the Kilauea series. B-B shows the crater of Kilauea with the agglomerate-filled throat of Halemaumau and also the small inward-facing cliffs southeast of Kilauea. C-C shows the fault-cliffs along the sea coast and the shallow graben of the southwest rift zone, also the hypothetical graben in the pre-Kilauea series. D-D shows Puu Kapukapu, a horst of pre-Kilauea lavas capped by the Pahala ash. (All profiles drawn from the photolithic proof sheets of the United States Geological Survey Topographic Atlas on the scale 1:31680 and exaggerated vertically about twice.)

gives no support to the hypothesis of marine origin, for the essential feature of wave cut terraces is their horizontality, but the Mauna Loa terraces slope to the southwest, one of the prominent ones about 900 feet in 8 miles. Profiles across the terraces show that the slope on their "treads" is no less than that above or below the terrace. (See fig. 5, section D-D.) There is not the slightest trace of up-raised beaches or reefs nor are there any signs of uplift in other parts of Hawaii in Kohala or on the slopes of Mauna Kea, where there have been no recent flows to mask them.

In addition to this negative evidence there is positive evidence of faulting. In a few places truncated flows and ash beds are exposed under the cascading flows, and along the tops of many of the palis there are open fissures in the recent flows, showing a repetition of movement along the old lines. (Such fissures might, however, be due merely to incipient landslides.) About one mile north of the Kapapala Ranch gate, beside the Volcano road is an area about three-quarters of a mile long which has not been covered by recent flows. At the upper end of this area at an elevation of 2100 feet is a narrow horst composed of horizontal, truncated flows and ash beds; at the lower end of the area is a long, closed depression, which is on the continuation of the faults forming the horst. This closed depression could only have been formed by faulting. Another small horst about 100 feet wide lies parallel to the road at an elevation of 2215 feet. A row of holes along its western edge marks the course of a fault. All these faults and terraces are exactly parallel to the series of fissures making up the southwestern rift system of Kilauea.

From Kapapala Ranch southwest to Honuapo, a moderate slope about two miles wide intervenes between the Kilauea lava field and the foot of a steep terrace, whose front edge rises from about 1800 feet at Honuapo to about 2600 feet near Wood Valley. At Honuapo the terrace swings around to the west past Naalehu. Mohokea and Wood Valley are great amphitheaters in the face of this terrace. Wood Valley is a flat-bottomed, steep-sided depression a mile wide and two miles long, whose form suggests an origin by faulting and landslide sapping. It may be significant that the sides of the valley are either parallel to the cross-faults of Puu Nahaha or are actual continuations of them. Mohokea is five miles across and five or six miles long and resembles Wood Valley except that it has several large hills or buttes inside its walls. The manner of origin of Mohokea is doubtful, but there is clear evidence of faulting across the valley.

It appears, then, that circumferential faults of large throw were formed along the Mauna Loa slope previous to the most recent lava flows. The exact age relation of the faulting to the Pahala ash is difficult to determine,

one reason being that it is apparently not the product of any one eruption but may have been deposited over a long period of time with considerable pauses intervening between eruptions. Good exposures are rare, but in one locality an ash bed a few feet thick continues down the slope of a terrace between two lava flows. The very thick bed of ash back of the half-way house, however, is cut by normal faults of a few feet displacement, and at several other places there is plain evidence of faulting in the Pahala series. Noble and Clark defined the Pahala series as a group of flows with interbedded ashes cascading over cliffs of the pre-Pahala lavas. They did not determine to what extent the Pahala ash was cut by faults. It seems probable that the main faulting took place toward the end of the Pahala period and was completed before the first of the post-Pahala flows.

The post-Pahala flows, which have cascaded down over the terraces, apparently have no great aggregate thickness, for in several places there are kipukas in them floored by the Pahala ash. Bird Park is a kipuka in the Keamoku flow about two miles from Kilauea, and its floor is covered by the Pahala ash. Pahoehoe flows from Kilauea cut across the foot of the kipuka and overlie the ash. Flows from Kilauea also abut against the steep, ash-covered slope where the Puu Oo trail reaches the foot of Mauna Loa. The Pahala ash is older than the surface flows from Kilauea at every place exposed. The Pahala ash does not appear in the walls of Kilauea crater and so is not only older than the surface flows but is older than all the flows exposed in the cliff at Uwekahuna. Apparently the Pahala ash lies on a slope against which the lavas of the Kilauea dome abut. If the Mauna Loa slope be projected toward Kilauea, it passes below the crater floor even if no allowance is made for possible buried terraces or for recent faulting in the Kilauea flows. The Pahala ash is not exposed in the 100-foot cliff of Puu Nahaha nor in the Great Crack, where 60 or 70 feet of lavas can be seen.

The post-Pahala flows of Mauna Loa interfinger with the Kilauea flows. The Keamoku flow from Mauna Loa ran down the valley between the two mountains and so overlies the Kilauea flows. From the lower end of the Keamoku flow to Kapapala Ranch all the surface flows from Kilauea are younger than the post-Kahala flows cascading over the terraces of Mauna Loa. Just south of Kapapala Ranch a great flood of lava came down from the north side of Wood Valley and continues over much of Kanenelu flat, but the sharpness of the topographic boundary shows that the amount of lava contributed to the Kilauea dome by Mauna Loa has been comparatively small.

THE CLIFFS OF SOUTHERN PUNA AND KAU

The southern part of the Kilauea area descends to the sea in a series of steps ranging in size from scarps 20 or 30 feet high to great cliffs as much as 1500 feet high. (See fig. 6.) These steps have been covered nearly everywhere by flows of the Kilauea series, which have cascaded over them; but in a few kipukas and in places on some of the highest and steepest cliffs where the curtain of flows has been stripped off by landslides or erosion, truncated horizontal flows and ash beds of the pre-Kilauea series are exposed. The cliffs are the scarps of normal faults, which have allowed segments of the island to sink toward the ocean. It is impossible to account for any of the scarps by marine erosion because of

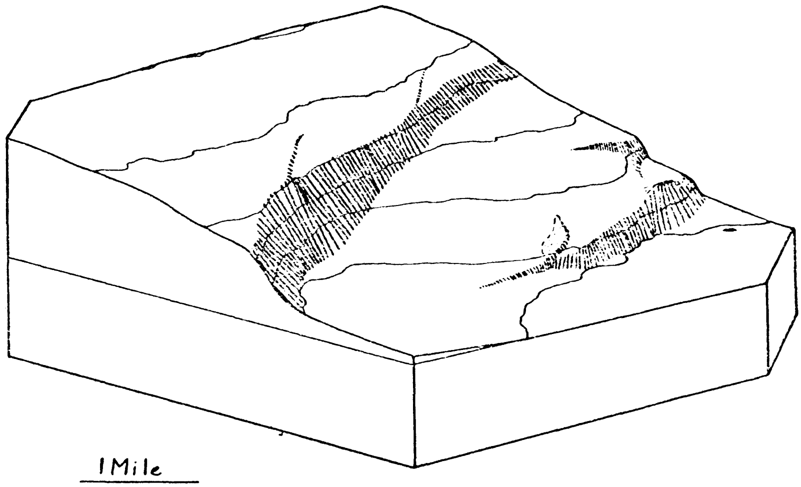

FIGURE 6. Block diagram of the coast south of Kilauea. The dotted area is the ash-covered top of Puu Kaone.

their size, discontinuity, and lack of horizontality; but there is abundant evidence of faulting.

Puu Kapukapu is a prominent yellow hill a mile and a half west of the abandoned landing at Keauhou. Its seaward face is a cliff 1053 feet high rising sharply from the water's edge; its landward side is also a cliff, which rises 130 feet above the flat lava covered area to the north. The crest of the hill is a narrow, east-west ridge in most places less than 100 feet wide and almost pinching out in some places where it is cut by faults of small displacement. The hill itself is composed of horizontal lava flows and ash beds of the pre-Kilauea series and is capped by a 20-foot layer of the Pahala ash. This narrow ridge of horizontal lava flows with a landward-facing scarp is a horst.

West of Puu Kapukapu is another yellow-topped hill, Puu Kaone, which is the southeast corner of a large fault-block. A hinge fault with progressively greater throw to the southwest has dropped the block lying between Puu Kaone and Puu Kapukapu, and another fault cliff along the south side of Puu Kaone separates it from a low strip along the coast. Lavas of the Kilauea series have flooded the country, but the high corner of the block of Puu Kaone has escaped. Along the northwest side of the hill its ash covering dips beneath the Kilauea flows. The fault which forms the southeast side of the hill can be plainly seen from the low country along the seashore and offsets a number of conspicuous aa flows and ash beds.

Along many of the lava covered palis, the Kilauea flows are cut by faults which were formed by repetition of movement along the old fractures. The faults forming the great cliffs, with the exception of the comparatively unimportant faults of recent times, are all older than the oldest flow of the Kilauea series and younger than the youngest flow of the pre-Kilauea series. All the flows overlying the Pahala ash, which is the topmost member of the pre-Kilauea series, cascaded over the fault-cliffs, but there are no ashes interbedded with the cascading flows. The relation in age of the Pahala ash itself to the faults is slightly in doubt. At no place was the Pahala ash found to continue down the face of a fault-scarp underlying the Kilauea flows. Ash covers parts of the slopes of the Kulalauula pali and Puu Kapukapu, but the surface portion at least of the ash in those places is reworked and contains ash pebbles. If the interval between the deposition of the Pahala ash and the first flows of the Kilauea series was long, the ash might have been completely eroded off the steep slopes (45° or more) before it could be protected by lava; but it seems more probable that the ash is older than the faults and so never covered the slopes.

THE PUNA RIDGE

The road from the Volcano House to Hilo passes for several miles over fresh, thinly-covered pahoehoe flows until it reaches a point about one and three-fourth miles southwest of Glenwood at an elevation of 2,580 feet. There the road leaves the fresh pahoehoe flows and continues over a surface covered by the Glenwood ash (p. 26), which has been described in an earlier part of this paper. An exposure beside the road at the contact shows the Glenwood ash passing beneath the pahoehoe flows, but the Glenwood ash does not appear in the walls of Kilauea crater. The boundary of the fresh surface flows northeast of Glenwood follows the line between the lands of Olaa and Keaau. The road from Olaa south to Pahoa leaves the old aa flows and ashes of the cane fields of Olaa near the railroad crossing and continues over fresh, thinly covered flows.

The fault cliffs of southern Kau and Puna continue east along the south side of the Puna ridge, and exposures of the pre-Kilauea series were found as far east as the cliff northeast of Ka Lae o Puki, where ash beds outcrop near the top of the cliff at an elevation of 950 feet. No ash beds are exposed in the pit-craters of Puna, which lie near the crest of the ridge, although the west pit of Makaopuhi gives a section of 700 feet above its talus slopes. A lava capping of this kind more than 700 feet thick in the center and thinning toward the north and south will account for the topographic form of the Puna ridge. (See fig. 5, section A - A.) The Puna ridge, then, has been built up by lava flows that originated along its crest line and is not the surface expression of a laccolith underlying eastern Hawaii as Daly (10, pp. 109-111) postulated. Neither the Kilauea dome nor the Puna ridge support the idea that Kilauea is fed by a satellitic intrusion; neither do they disprove it.

The flows that built the Puna ridge had three possible sources: the pit craters, the cones, and the fissures. There is no bending of the contour lines around the pit craters to show that lava ever overflowed their walls; but it is not impossible that overflow occurred at some of them as at Halemaumau. Large volumes of lava have certainly been erupted from some of the cones as shown by the bending of the contour lines around them, for example, Kane Nui o Hamo. Many flows also came from fissures. Near Makaopuhi are the small fissure flows of 1840, 1922 and 1923, and in eastern Puna is the large Nanawele flow of 1840. The topographic maps of the United States Geological Survey, especailly of the Wahaula Heiau and Puna Forest quadrangles, show many aa flows originating near the lines of fissures and flowing down over the palis to the south, and Ellis gives legends of flows in Puna (13, pp. 207, 214, 218).

KILAUEA AND THE RIFT LINES

Many faults younger than those of the Mauna Loa slope and those of the cliffs of southern Puna and Kau break the Kilauea lavas. Kilauea crater itself is a downfaulted sink or caldera two miles and a half long and two miles wide in the top of the flat lava dome. (See fig. 7.) There are two series of faults: a dominant northeast-southwest series, which includes the main faults of the northwest and southeast walls of the crater as well as the fissures of the southwesterly rift system; and a second series peripheral to the crater. Blocks outlined by these faults sunk to form the crater, but all the blocks did not sink at the same time or to the same depth. Some blocks along the rim are outlined by open fissures but have not yet begun to sink, and others have slipped down a little way and form fault terraces like those at Uwekahuna and below the Volcano House.

A large area around the crater has been included in the sinking so that there are small inward-facing cliffs surrounding the crater. If the original lava dome were restored, its summit would be over the northern part of the crater; therefore if the crater originated in the summit of the dome, it has grown toward the southwest by the sinking of additional blocks, a process which is going on at a slow rate even at the present time.

The walls of Kilauea crater consist almost entirely of horizontal lava flows, but a few small intrusive bodies and one ash bed are included. The exposure of the ash bed is of considerable interest, for it shows the ash

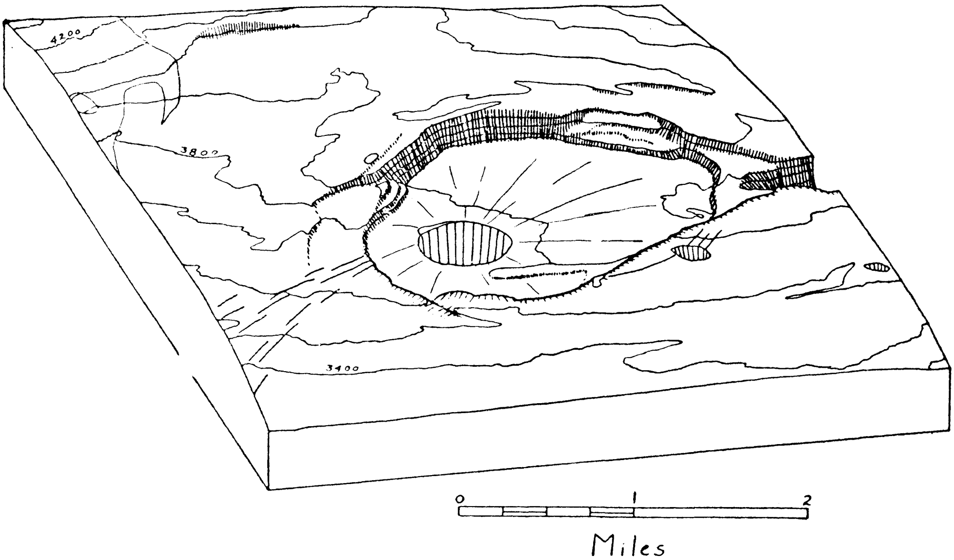

FIGURE 7. Block diagram of Kilauea crater.

lying on the surface of an unconformity caused by a fault with about 75 feet of throw. Flows younger than the Uwekahuna ash have covered the fault scarp and built the 450-foot section of lavas making up the Uwekahuna cliff above it. This unconformity, which is the only evidence showing that there was more than one period in the formation of the lava dome, shows an earlier collapse like the one which formed the present crater followed by a period when lava flows were filling the crater and overflowing its walls as Halemaumau has been doing in recent times. The earlier crater had a slightly different position from the present one, but its depth and extent are not revealed.

Recent pahoehoe flows, especially those of 1919 and 1921, cover the crater floor, which is the surface of a gently sloping dome, and whose only irregularities are those common to lava flows. At the summit of the dome

is Halemaumau, in recent years a lava lake, but since the collapse of 1924 a yawning pit 3400 feet long, 3000 feet wide, and 1350 feet deep. The walls of Halemaumau, like those of the outer crater, consist largely of horizontal flows, but Halemaumau has several small dikes and some large, irregular intrusive bodies. No ash layers, not even that of 1790, appear in the walls, but this observation is not surprising, for a greater thickness of lavas than is exposed in Halemaumau can be accounted for by the eruptions of the nineteenth and twentieth centuries. Dana describes the wall at Uwekahuna in 1825 as about 900 feet high, and the bottom of the larger inner crater which existed at that time as about 400 feet below the base of the cliff. Since that time the floor of the crater has been built up by lava flows so that the cliff at Uwekahuna is only 450 feet high, and the rim of Halemaumau is a little less than 400 feet below the highest point of the crater rim. At least 900 feet of lava then, which is about all that shows above the talus slopes, is younger than 1825, but the great collapses following the eruptions of 1832, 1840, and 1868 far more than account for the remaining 400 or 500 feet. Jaggar estimates that in the great collapse of 1924 seven billion cubic feet of rock sank several thousand feet into the mountain, but only 1/253 of that amount was ejected as ash (25). The pit craters were also formed by engulfment, mostly with no ejection of material. Some of the craters have been partly filled by lava since their formation, but in others, for instance the Devil's Throat, there is no sign of lava.

The southwesterly rift system of Kilauea is a continuation of the northeast-southwest faults and fissures of the crater. Most of the fissures of the rift system are open tension cracks with no relative displacement of the opposing walls either vertically or horizontally. In places blocks between two fissures have sunk and made shallow graben. The few fissures along the west side of the rift zone whose walls have been displaced have had their southeastern sides thrown down, mostly only a few feet, but Puu Nahaha is a conspicuous faultcliff 150 feet high, the edge of two fault-blocks, each bounded by a fault on its eastern and southern sides and tilted down to the northwest. The fault bounding the southern block bends around at right angles to its former course and dies out, and as the fault dies out, the deformation changes from a clean fault break to what would have been a monoclinal fold in more pliable rocks. Between the upthrown and downthrown blocks is a block tilted 30 or 40 degrees and fractured into small blocks but with each block still in its proper place; an open fissure separates the sloping block from the upthrown block. This kind of fault scarp is common in other parts of the lava fields.

Along the east side of the rift zone a series of fissures extends north-

east from near the Kamakaia Hills but bends more and more to the east as it approaches Kilauea until it finally swings into parallelism with the line of pitcraters and continues on into the fissure system of Puna. Fault cliffs with a maximum height of 60 feet and downthrown on the northwest are almost continuous from the Kamakaia Hills to Pauahi crater. The fault scarps along the western and eastern sides of the rift zone outline a shallow, wedge-shaped graben four miles across and sixteen miles long with its broad end at the crater and its point near the Kamakaia Hills. Besides the fissures of the two rift systems there are many other faults in the Kilauea lavas. Some of them have been produced by repetition of movement along the lava-covered faults of the older system, and most of the others are parallel to the older faults. Faulting in the Kilauea lava has not been confined to any definite period, but faults were formed during the very early history of the volcano in flows older than the Uwekahuna ash, and movements occur at the present, some of them accompanied by earthquakes. The younger period of faulting, as distinguished from the pre-Kilauea faulting, has produced Kilauea crater, the pit craters, and many faults and fissures.

Kilauea crater must have existed in much its present form before 1790, for if there had been any great change, such as the formation of the crater, at that time it would certainly have been mentioned by the natives who related the history of Kilauea to Ellis in 1823. The idea advanced by Walther Penck (29, pp. 194-195) that Kilauea may have originated as the greatest of the pit-craters in 1790 by a maar-explosion is quite untenable, because older ash deposits prove that Kilauea existed before that time, and because explosions have only rarely accompanied the formation of pit craters in Hawaii. The age of the crater with regard to the oldest surface ashes is somewhat in doubt; Powers (31, pp. 238-240) suggested that the oldest ashes may be older than the crater, but the following evidence favors the idea that the ashes are younger:

1. Deposits of ash have formed a slope against the low cliff forming the crater wall southwest of Halemaumau.

2. The ash deposit at the foot of the Volcano House trail is about 15 feet thick, but that at the top of the cliff is only 6 feet thick. The ash at the foot of the cliff is coarser and rests on a talus-covered slope.

3. No flows are interbedded with the surface ashes although the ashes were deposited during a long period, probably of a few hundred years. (Powers's statement that the Keamoku flow overlies the older Kilauea ashes is erroneous. He evidently mistook the Pahala ash for some of the surface ashes of Kilauea.) By analogy with the explosive eruption of 1924 it

should be expected that the great explosions of prehistoric time have accompanied great collapses such as may have initiated the present crater.

Some movement has undoubtedly occurred since the deposition of the ash, for many open fissures cut it. The formation of the crater was not a sudden catastrophic collapse, however, but a gradual widening which is still in progress. In times when the crater was hundreds of feet deeper than it is now, its walls must have retreated much more rapidly.

The top flows of the crater walls have fresh surfaces and the oldest surface ash may not be more than five hundred years old. (See p. 35.) Native traditions recorded by Ellis (13, p. 184) in 1823 further support the idea that Kilauea ended its superfluent stage within the last few hundred years. Ellis says:

> As eight of the natives with us belonged to the adjoining district, we asked them to tell us what they knew of the history of this volcano, and what their opinions were respecting it. From their account, and that of others with whom we conversed, we learned that it had been burning from time immemorial . . . , and had overflowed some part of the country during the reign of every king that had governed Hawaii; that in earlier ages it used to boil up, overflow its banks, and inundate the adjacent country; but that for many kings' reigns past it had kept below the level of the surrounding plain, continually extending its surface and increasing its depth, and occasionally throwing up, with violent explosion, huge rocks or red-hot stones. These eruptions, they said, were always accompanied by dreadful earthquakes, loud claps of thunder, with vivid and quick-succeeding lightning. No great explosions, they added, had taken place since the days of Keoua [the eruption of 1790]; but many places near the sea had since been overflowed, on which occasions they supposed that Pele went by a road underground from her house in the crater to the shore.

The inward facing cliffs around Kilauea were formed during the same general period of faulting as the walls of the crater and are not the ancient boundaries of former craters. The pit craters and other faults also have been formed since the superfluent stage of Kilauea, for they cut the Kilauea lavas and no flows from the crater cascade over them. A flow older than the ash of 1790 does cascade over Puu Nahaha, but it is probably a flow from a fissure. The floor of the eastern pit of Makaopuhi is covered by small saplings, which could easily have grown within two hundred years even if the spread of vegetation had been very slow; the western pit has formed since the floor of the eastern pit "froze" and so must be very young. The two main talus funnels of Pauahi crater are also of different ages; one is lined by small trees, and the other is bare. Faults were formed during the earthquakes of 1868 and 1924.

The principal structural features of the Kilauea region are shown in figure 5. The faults shown in the sections are revealed by topographic breaks, by open fissures, or by actually observed offsets. They are all normal faults but the amount of dip of their fault planes is largely hypo-

thetical. The cliffs formed by some of the pre-Kilauea faults have slopes as low as 45° or 50°, but the faults of the crater and other recent faults are steeper, most of them nearly vertical. The thicknesses shown for the Kilauea series are also quite hypothetical but may be taken as minimum estimates. There are very few data for fixing the thickness of the Kilauea flows along the southwest rift, but many eruptions have occurred there, so perhaps the series is considerably thicker than shown in the sections. In drawing the sections shown in figure 5 it was assumed that there was a constant slope of the pre-Kilauea surface from Mauna Loa to the sea, gradually flattening but with no reversals. This assumption is justified by the continuation under the area of the older series of flows from Mauna Loa.

CONCLUSIONS

THE GEOLOGICAL HISTORY OF KILAUEA

The geological history of Kilauea may be summarized as follows:

1. The eruption of the pre-Kilauea lavas and ashes built up a flat lava dome whose summit was somewhere inside the area enclosed by the 7500-foot contour line of Mauna Loa. This accumulation was not uninterrupted, but in the vicinity of Pahala there was an interval of faulting and erosion between the pre-Pahala and Pahala lavas.

2. Normal faulting during and after the Pahala epoch formed scarps along what is now the southwest slope of Mauna Loa. Faults were probably formed at this time also along the line of the Puna ridge, for fissures along that line have been important conduits for lava since very early in the history of Kilauea. The faults along the Mauna Loa slope are roughly parallel to the elongation of Mauna Loa and to its southwest rift, which is one of the fundamental tectonic lines of the region, but they apparently do not continue northeast of Kilauea. The series of fissures diverging from the southwest rift of Kilauea and continuing through Puna is nearly parallel to the northeast rift of Mauna Loa, and the influence of the directions followed by these two sets of riftlines is again shown in the south coast of the island. The whole structural history of southeastern Hawaii has depended on the tendency for slices of the island bounded by faults parallel to these directions of weakness to settle toward the ocean.

The origin of the primary riftlines along these directions is too speculative a problem to be discussed here and the cause of the sinking is also beyond any proof, although it may be suggested that the sinking was caused by the overloading of the earth's crust over a wider area than was supported by an underlying magma reservoir. Local or temporary withdrawals of support might lead to sinkings such as formed the craters, and the loss of an active upward pressure following the congealing of the magma reservoir may have led to the extensive faulting suffered by the other Hawaiian islands in which volcanism is extinct.

It is possible that a graben was formed during the latter part of the faulting, along what is now the southwest rift of Kilauea and corresponding quite closely in position with the shallow graben in the Kilauea series (p. 12). The parallelism between the fissures and small faults cutting the Kilauea flows and the older faults shows that the younger faults have

been formed by a repetition of similar movements, probably in part along the same lines. The frequent occurrence of large fissure flows along the southwest rift shows that fissures of primary importance have existed there all during the accumulation of the Kilauea series and so gives some grounds for the hypothesis that the shallow graben at present existing along the rift zone is merely the reflection of a larger graben that was buried by the Kilauea flows.

3. Kilauea volcano originated at the head of the graben probably by collapse accompanied or followed by the eruption of the Pahala ash. The Pahala ash is probably of Kilauean origin, no lavas or ashes from Kilauea are known older than the Pahala ash, although it is of course possible that Kilauea had started to build up a cone, now completely buried, before the eruption of the Pahala ash. Dr. Jaggar suggested to me that possibly the ash formerly exposed in the northwest wall of Kilauea corresponds with the Pahala ash. Powers (31, p. 230) states that 17 feet of ash was exposed but that the base was hidden. His description, however, is not sufficiently detailed to allow comparison with the Pahala. If this ash bed does correspond with the Pahala, the thickness of Kilauea lavas at the crater is less than shown in the cross-sections of figure 5. It is unfortunate that no description exists of the rocks exposed in the crater walls in the early part of the last century, when the floor was much lower than at present.

The process of collapse by which Kilauea may have originated is shown in several stages by the pit craters of Puna and Mauna Loa and by Halemaumau itself. The flat topography around the pits as well as the lack of ejected material definitely prove that they were formed by collapse rather than by explosion, and the arrangement of the Puna craters in a line which is paralleled in part by a series of cracks shows their dependence on a fissure. The crater of Pauahi shows its dependence on a fissure even more clearly, for it is formed by three adjoining pits all in line. The earliest stage of the process of collapse is shown by the Devil's Throat, a hole 250 feet deep and 125 feet across the bottom but only about 30 feet across the top, which is plainly due to undermining from below. Most of the pit craters show the next stage in which a slightly larger area is undermined so that the walls cannot stand in the unstable, overhanging position of the walls in the Devil's Throat, but instead break back to form the usual funnel-shaped pit. Undermining of still larger areas permits the bodily sinking of large blocks as in Kilauea and Mokuaweoweo.

Makaopuhi, the largest of the pit craters, is broken into the side of a large cone, Kane Nui o Hamo, and several of the other pits are near to cones. The association probably does not mean that the extrusion of the

lava that formed the cone created a void, for that would demand some very unusual type of mechanism, but rather the existence of a cone points to the presence near the surface of a lava filled fissure, which would be a locus of weakness when the lava withdrew.

The formation of some of the pits was followed by the rise of lava in them and the formation of lava lakes, as in Keanakakoi, Alealea, and Makaopuhi, but in these craters the lakes quickly congealed whereas in Kilauea, perhaps because it is situated on a larger fissure, the lake persisted and built up a cone by overflowing.

4. The cliffs along the southern coast of Puna and Kau were formed by normal faults with displacements up to at least 1500 feet. This faulting took place before any flows from Kilauea had reached the region but probably after the eruption of the Pahala ash.

5. Flows of the Kilauea series built up a dome both by overflows from the crater and by fissure eruptions. The dome was not built up continuously, but the building was interrupted at least once by a collapse like that shown by the unconformity beneath the Uwekahuna ash. There is no reason for believing that Kilauea was ever capped by cinder cones; the lava dome was probably much like the dome forming the floor of the present crater, and, like it, had a lava lake at its summit.

6. A period of great collapse gave birth to the present Kilauea crater and also at different times to the pit craters and many fissures and faults cutting the Kilauea series. The crater did not attain its full size at once but according to the native traditions grew gradually, explosive eruptions occurring during the period of growth.

7. During the period from the eruption of 1790 to 1924, Kilauea was building up the floor of its crater by overflows from Halemaumau and was also slowly adding to the size of its dome by fissure eruptions on its flanks. In 1924 there was a great collapse in Halemaumau accompanied by explosive ash eruptions. Two months later lava again rose into the pit but only for a few days, and since that time Kilauea has been quite dormant.

No liquid lava was in the pit during the eruption of 1924; no glow was seen, the ash consists entirely of mineral fragments, and there are no bombs among the coarser ejecta. In 1790, however, there were, according to native accounts, great fountains of lava, and the accounts are corroborated by the ashes of that eruption, which contains bombs, thread-lace scoriae, and glass fragments. Liquid lava also was present during the eruptions before 1790; in fact the older yellow ash south of the crater is almost entirely glass.

It has interested me to consider the possibility of repetition in the cycle of events in the history of Kilauea. Faulting along the Mauna Loa slope, which may have originated Kilauea, was followed by the eruption of the Pahala ash. The next interruption was the downbreak recorded in the Uwekahuna ash (which, however, was deposited somewhat later than the faulting). The older surface ashes were erupted after the formation of Kilauea, during a long period when the crater was extending its area. While conditions during the eruption of 1790 are not known, in 1823 there was a very large, deep, inner crater, which may have been a relic of a collapse in 1790. Finally, the explosions of May, 1924, followed a great sinking of the lava lake. The agglomerate around Alealea crater originated in the same way. Many great collapses, however, like those of Kilauea in 1832 and 1868 and those which formed most of the pit craters, were not accompanied by explosions, but the complete cycle seems to have been: collapse, probably caused by a withdrawal of lava; explosive eruptions; return of lava, leading to overflows.

COMPARISON OF KILAUEA WITH OTHER VOLCANIC REGIONS

Many volcanic regions of the world resemble Kilauea in some degree. The widespread occurrence of fault depressions in volcanic regions has been emphasized by Friedlander (15), who believes that subsidence is the primary agent in the formation of all large craters, that no caldera more than two kilometers across has been formed by explosions alone, and that the distribution of volcanism in space and time has largely been conditioned by tectonic happenings. The great Aniakchak crater in Alaska has recently been attributed by Smith to explosion (33), but the crater is little known and further investigation may show that subsidence had an important part in its formation.

Craters most like Kilauea are Mokuaweoweo and some of the craters of Iceland. In fact, Iceland of all regions described in geological literature most nearly resembles Hawaii. The foundation of Iceland (1) is a plateau of basalt lavas built up in early Tertiary and broken by block faulting toward the close of the Miocene epoch. In Pliocene numberless outbursts gave rise to a great deposit of palagonite tuff and breccia, which is overlain by recent lavas erupted from fissures and to a smaller degree from great shield volcanoes like Mauna Loa. Series of parallel open fissures, some of them the sources of fissure eruptions, are common in Iceland as in Hawaii, and another point of resemblance is in the prevalence of normal faults; in fact the sequence of events in Iceland the block faulting of the older Tertiary lavas, the eruption of the Pliocene fragmental deposits, and the lava flows of Pleistocene and Recent time—a repetition on a much larger

scale of the history of Kilauea. Normal faulting such as occurred in Hawaii and Iceland is a feature of several regions where great amounts of basalt have been poured out, among them the Hawaiian islands of Molokai and Lanai (41, pp. 45-48; 27, p. 13) and the Isle of Skye (16, pp. 8-9).

Volcanoes like Kilauea in structure have not been recognized in many places in older geological formation, but two, Glencoe and Mull, have been described from western Scotland. Glencoe (6) is a deeply dissected volcano of Old Red Sandstone age with a caldera five miles wide by nine miles long, which was formed by the sinking to a depth of 1000 feet or more of a block enclosed by a vertical or slightly outward-dipping ring-fault. The agglomerates, andesites, and rhyolites of the volcano have been almost entirely removed by erosion except within the sunken block. The Cruachan granite was intruded into the floor of the caldera as it sank and also along the bounding fault, which was obliterated by the granite at the southeast corner of the caldera. Clough, Maufe, and Bailey compare the Glencoe subsided area with the crater of Askja (34) in Iceland, but it is also quite analogous with Kilauea.

The volcanic center of Mull in western Scotland not far from Glencoe is the wreck of a lava dome of the Kilauean type, whose similarity in some respects to Kilauea was recognized by Bailey (2) and also by Jaggar (24). During its early history this lava pile is believed to have had the form of a low Kilauean dome with a double central caldera five or six miles across and repeatedly renewed by subsidence. Each part of the caldera was surrounded by ring fractures, which allowed the central blocks to drop down and which became filled by dike intrusions as at Glencoe. The southeastern caldera is intruded by a complex concentric series of these ring dikes, most of them forming only a small part of a complete ring, others forming a nearly perfect ring. The inclination of most of the dikes is not known, but in two places the Loch Ba felsite dike, a nearly complete ring surrounding the northwest caldera, dips outward 70 or 80 degrees; in another place it dips outward at about 45 degrees; but elsewhere it appears to be steep. Anderson concludes after a theoretical discussion (2, pp. 11, 12) that the ring dikes follow steep fissures shaped like the curved surface of an artillery projectile, with their apices uppermost. The fissures, he supposes, were formed when support was withdrawn from below. In Hawaii the corresponding ring fractures bounding the calderas dip steeply inward and have plainly been caused by the withdrawal of support, probably occasioned by the sinking of the underlying lava column. The difference in direction of inclination between the ring faults of Kilauea and Mokuaweoweo and those of Mull and Glencoe may be due to the difference in the level at which they are revealed by erosion. A block

bounded by an inward-dipping conical fracture could not sink, yet the floor of Kilauea has sunk at least a thousand feet. A block bounded by a vertical or outward-dipping fracture, however, could sink easily, but if a vertical or outward dipping fracture reached the surface, there would probably develop secondary inward dipping faults by which the walls on the upthrown side of the main fault would attain a stable angle. It seems probable then that the ring fault bounding Kilauea may grow steeper with depth.

The pit craters apparently did not form by the sinking of large blocks of the crust, but rather by the complete removal of support close to the surface under smaller areas and by a sudden collapse such as occurs when a plug is drawn from the bottom of a box full of loose sand and a funnel-shaped depression is formed. The opening into which the material formerly occupying the pit collapsed need not have been cylindrical but may have been a dike-like fissure as is indicated by the alignment of the Puna craters. Such a cavity might be formed by the sinking of the lava column out of a rift or by the sinking of a subcrustal block.

Another feature common to Kilauea, Mauna Loa, Iceland, Glencoe, and the Tertiary volcanic regions of western Scotland is the occurrence of swarms of parallel fissures. In Scotland these fissures are now occupied by dikes; in Iceland and Hawaii they show at the surface as open cracks, but many of them have poured out lava flows so that deep erosion would reveal dikes there also. None of the dikes or fissure swarms mentioned show any tendency toward a radiating arrangement around a center. The great Tertiary dike swarm of Scotland is found over an area about 360 miles long and over this whole region preserve a remarkably constant northwest trend. Although the volcanic center of Mull lies in this line of dikes, it cannot have been the cause of them, but instead both depend on the fundamental structure of the region. The same relation is true at Kilauea.

Most of the fissures of Kilauea and Mauna Loa and also those of Iceland are tension cracks, whose walls have not been relatively displaced either vertically or parallel to the crack. The fissures of the Kilauea system are not all of the same age, for some have given birth to fissure eruptions in ancient times, and others have opened within the last years. In 1920 a fissure of this kind opened southwest of Kilauea (Pl. II); it extended farther day by day and from it in places lava came to the surface and formed the great Mauna Iki flow and some smaller flows. (See fig. 1.) The opening of the rift and the lava flow occurred during a time when lava stood very high in Halemaumau and when tilt measurements showed that the whole dome of Kilauea was swelling, apparently pushed up by the rising magma below (21, pp. 190-194). Such a swelling of the volcano

accompanied by the opening of tension cracks might be repeated again and again.

Other fissures supposed to be caused by upward magma pressure are those occupied by the cone-sheets of Mull and Skye. They are ring fractures dipping inward at 30° to 45°, but ring fractures having such a low angle of dip have not been recognized in Hawaii. In Hawaii as in Mull there have been explosions along dikes (37).

There are still further similarities between Kilauea and the plateaus of Mull and Skye, for all three are built up of comparatively thin basalt flows and in all three the volcanic activity was ushered in by a period of explosive eruptions, which produced the Pahala ash at Kilauea, the basal mudstone at Mull and the basal agglomerates in Skye. Harker (16) concludes that the basalts of the plateau are the products of fissure eruptions, and denies the existence of a great central volcano. His grounds for assigning the basalts to fissure eruptions are: (1) the enormous volume and extent of the lavas as a whole in contrast with the limited dimensions of the several flows which collectively build up the pile; (2) the almost total absence of the pyroclastic accumulations which are the chief products of most volcanic vents of the central type; (3) the fact that the lavas, as a group, show no indication of thickening toward particular centers and dying out away from such points. The authors of the memoir on Mull have recognized that the criteria enumerated by Harker prove that the volcanic centers of western Scotland were not strato volcanoes like Vesuvius. However, they may be lava domes like Kilauea. The authors further point to the fact that in Iceland central eruptions and fissure eruptions occur in the same area—a statement applicable also to Hawaii. The work of Bailey and his colleagues should call attention to the fact that central eruptions and fissure eruptions are not mutually exclusive phenomena; the only essential difference between the lava eruptions that formed Mauna Loa and Kilauea on one hand and the Snake River plains on the other, is that in Hawaii some vents persisted long enough to build large lava domes, but in Idaho all the vents were short lived. A similar conclusion is reached by Stearns (36, pp. 362-363).

Not only are Mull and Glencoe volcanoes that have been much more deeply eroded than Kilauea, but they are also volcanoes that had reached a much more advanced stage of development and complexity before becoming extinct. In Mull the eruption of the Plateau and Central types of basalt lavas was followed by a long and complicated period of intrusions during which there were two cycles of change from a basic to an acid magma followed by a final return to basic. At Glencoe the volcanic eruptions of andesite and rhyolite were followed by large intrusions of granite.

At Kilauea, however, there is no sign either in the lava effusions or in the ejected fragments that any but basaltic magma ever played a part in its history. Moreover it does not seem probable that magmatic development in Hawaii could ever reach the state of complexity found in Mull, for in the most deeply dissected parts of the Hawaiian islands where volcanism seems to be dead, for example in Kauai and West Maui, there is no evidence of anything but very slight differentiation, and the simplicity of the rocks of the oceanic islands is a generally recognized fact.

Kilauea would resemble more closely the volcanoes of Scotland if erosion had removed all topographic evidence of a crater. To destroy the crater existing in 1925 erosion would involve planing off the mountain to the level of the bottom of Halemaumau, which is about 1700 feet below the top of Uwekahuna. Erosion to this level would remove all the lavas of the Kilauea series from the walls of the crater and the surrounding country, and as at Glencoe the younger volcanic series would be preserved only inside the ring fault bounding the main crater and perhaps in Kilauea Iki. The surrounding country would be underlain by the almost flat lavas and ash beds of the pre-Pahala series of Mauna Loa, which would be cut by swarms of dikes along the rift lines and probably by some small irregular dikes, like those in the north wall of the crater, around Kilauea.

The region of the crater floor would present many features of interest. There are no records of eruptions from the bounding ring fault of Kilauea, but in Halemaumau lava has frequently risen along the wall of the pit, and by analogy with Mull and Glencoe ring dikes would be expected. In the place of the pit of Halemaumau would be an agglomerate neck 3,400 by 3,000 feet across full of huge basalt blocks weighing many tons partly enclosed in the lava which foamed up through the talus in July, 1924. Irregular, gabbroid intrusive bodies and dikes would cut the lavas of the crater floor.

Other agglomerate necks besides the one of Halemaumau would show the positions of the pit crater. Agglomerate necks are usually regarded as evidence of explosive eruptions but in Hawaii they have been formed by collapse. Criteria which might be used in deciding whether an agglomerate neck was produced by explosion or collapse are: the kind of fragments composing the agglomerate, and the size of the fragments. From a knowledge of the materials composing the agglomerate and of the local stratigraphy it may be possible to determine whether the fragments have moved up or down to their present resting place and how far they have moved. The size of the fragments may also aid in telling the direction of the movement. The great size of some blocks in the vent agglomerates of Skye led Harker to believe that they had fallen in from above. The surface agglomerate of

Kilauea includes blocks weighing as much as 14 tons, but in the talus in Halemaumau there must be whole slices from the walls, which are much larger, and the talus at the bottom of Makaopuhi contains many bowlders weighing 20 or 30 tons.

The lavas in the lower part of the crater floor are probably somewhat altered by solfataric action such as has produced the sulphur banks near the Volcano House and along the southeast side of the crater, and also produced the alteration in some of the reddened blocks ejected from Halemaumau.

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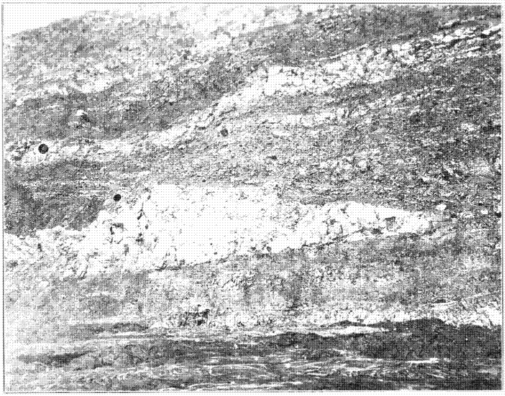
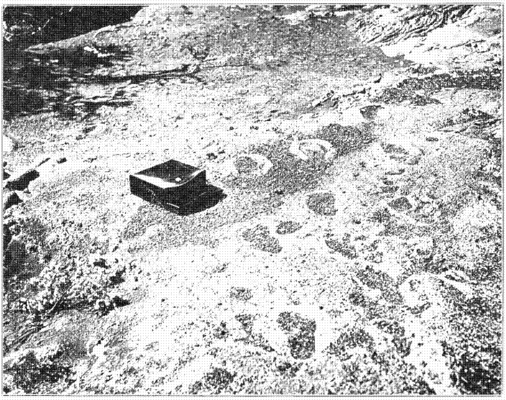
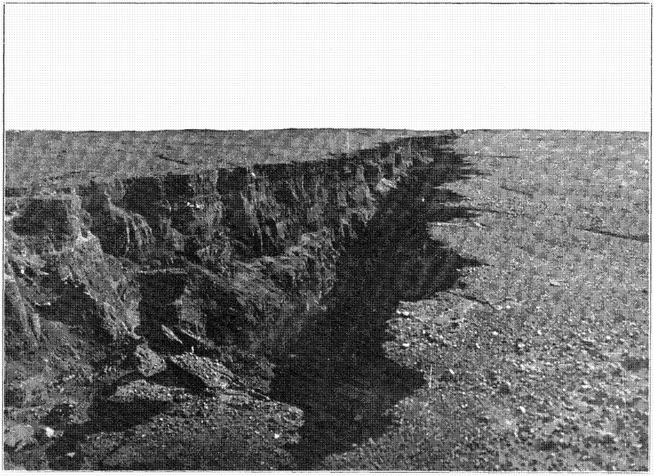


A, part of the crater wall of Kilauea, including the eastern part of the Uwekahuna intrusive body (photograph by R. H. Finch).



B, fossil human footprints in the pisolitic ash of 1790 southwest of Kilauea (photograph by T. A. Jaggar).



OPEN FISSURE IN THE KAU DESERT SOUTHWEST OF KILAUEA. THE SURFACE IS COVERED WITH ABOUT FIFTEEN FEET OF ASH.

To renew the charge, book must be brought to the desk.

TWO WEEK BOOK

DO NOT RETURN BOOKS ON SUNDAY

DATE DUE

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